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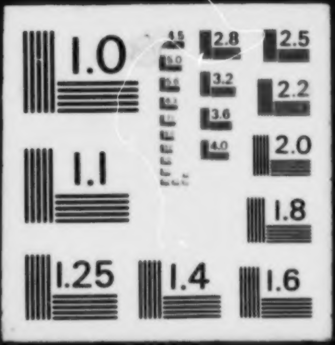
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Northwestern Univ, Evanston, Ill Dept of Civil Engineering

Prepared for

Municipal Environmental Research Lab, Cincinnati, Ohio

May 78

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One commonly used alternative to the open water disposal of polluted maintenance dredgings is to place these sediments in diked containment areas to form landfills of marginal value. This study was directed toward evaluating quantitatively the engineering characteristics of dredged materials as they affect their potential usefulness in a landfill. The work was limited to fresh water dredgings from Great Lakes harbors, and most of the effort was centered around four disposal sites in the Toledo (OH) harbor; however, the results are considered to be applicable to a wide range of fresh water maintenance dredgings.

The disposal of dredged sediments in diked containment areas does improve the overall quality of the surrounding surface waters, but it is not clear whether the degree of improvement realized is sufficient to justify the considerably higher costs involved. In addition, the low initial shear strength of these high-water-content, organic materials under natural conditions, along with their slow rate of strength increase with time and their associated large volume changes, seriously limit the usefulness of landfills composed of dredged materials. Unless special steps are taken to improve the quality of these materials, their use will be restricted largely to wildlife refuges, parks, recreational areas, parking lots, access roads, and the construction of light buildings with flexible structural joints and flexible floors which would allow several inches of total settlement and a few inches of differential settlement.

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Summary Technical Report

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment for public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communications link between the researcher and the user community.

The need to protect the ecology of the Great Lakes and the other waterways of the United States has led to a variety of problems concerned with the dredging and disposal of increasing volumes of polluted dredge spoil in areas of high population density and industrial development. One commonly used alternative to open water disposal is to place these polluted sediments in diked containment areas to form landfills of marginal value. However, due to the high costs involved, the scarcity of land, and other environmental and economic considerations, these landfills should desirably serve some useful purpose. Accordingly, this study was directed toward evaluating quantitatively the engineering characteristics of dredged materials as they affect their potential usefulness in a landfill.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

ABSTRACT

This research program was initiated with the overall objective of evaluating the usefulness of dredged sediments as landfill material. The study is limited to the deposition of polluted fresh water dredgings from the Great Lakes area, and the major effort was centered around four disposal sites in the harbor serving Toledo, Ohio.

A comprehensive sampling and testing program was undertaken in the field and in the laboratory to determine the engineering characteristics of hydraulically placed maintenance dredgings and the water quality effects associated with a typical dredging and disposal operation. Samples were taken from seven Great Lakes harbors, but the vast majority of the laboratory tests and virtually all of the field work were performed on dredged materials from the Toledo area. However, these materials are considered to be representative of maintenance dredgings that are found at a number of fresh water ports.

Several thousand chemical analyses were conducted to assess the pollution potential of dredged materials under chemically treated and non-treated conditions. Several series of flocculation-sedimentation, sedimentation-leaching, repeated leaching, and evaporation tests were conducted to study the possibility of stabilizing these materials with chemical additives and to evaluate the effects, if any, of such chemicals on the leachates. Numerous index property tests were performed for classificatory purposes, and several correlations among different properties and the results of the index tests were established. An extensive series of conventional and unconventional consolidation tests was conducted, and a number of permeability and electro-osmosis tests were performed to complement the permeability data backcalculated from the consolidation tests. Laboratory strength determinations made by means of miniature vane, cone, and unconfined compression tests were compared directly with field strength data determined by field vane tests.

An extensive field monitoring program was undertaken to evaluate the effects of a typical dredging and disposal operation on the water quality parameters of the environs. The major thrust was directed toward investigating the performance of one particular disposal area which was filled with almost a million cubic yards of dredgings over a two-year period and three other similar disposal areas which had been used during the preceding decade. Periodic vane shear tests were conducted in two of the areas, and settlement plates were installed at one site to determine the time-dependent variations in the strength and settlement, respectively. Several in situ permeability tests were conducted on the foundation soils and the dredged materials to evaluate drainage conditions. Finally, a one-dimensional mathematical model was developed to assess the relative importance of gravity drainage and

cont'd

evapotranspiration on the desiccation and consolidation of a landfill composed of maintenance dredgings.

This report was submitted in fulfillment of Grant R-800948 by Northwestern University under the partial sponsorship of the U. S. Environmental Protection Agency. This report covers a period from September 1970 to December 1974, and the work was completed as of September 1977.

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SECTION 1

PERSPECTIVE

The development and maintenance of the navigable waterways in the United States have been assigned by Congress to the U. S. Army Corps of Engineers. The extent of this task is manifested by the fact that approximately 19,000 miles of waterways and 1,000 harbors must be kept open in order to accommodate our nation's commercial water traffic. The single greatest problem in dealing with this task is the continuous accumulation of bottom sediments through the natural transport phenomena that occur in these waters. About 300,000,000 cubic yards of bottom sediments must be dredged annually to maintain these waterways and harbors, and an additional average of 80,000,000 cubic yards are dredged to develop new projects or to increase the capacity of existing systems. Of this amount approximately 11,000,000 cubic yards are dredged from 115 Great Lakes harbors. Current (1974) annual costs for these operations are estimated to be about $200,000,000, and the average unit cost of dredging is about 50 cents per cubic yard although the latter can vary from about 20 cents to tens of dollars per cubic yard, depending on the circumstances.

PROBLEMS OF DISPOSAL

Until recently, most of these materials were deposited in the open waters at selected disposal areas located sufficiently near the harbors to minimize dredging costs, but far enough away to avoid interference with water intakes, beaches, and other facilities. However, as a consequence of population growth and industrial development in certain regions, the sediments dredged from nearby harbors and channels have become increasingly polluted, and concern about the impact of these polluted dredgings on the environment has been expressed publicly through appeals to halt the open water disposal of such materials. For example, the Rivers and Harbors Act (Public Law 91-611, Section 123) of 1970 requires that all polluted sediments dredged from the Great Lakes region be placed in diked containment areas. Accordingly, the Environmental Protection Agency, which is charged with the responsibility for safeguarding the environment through the imposition of appropriate controls on waste disposal, has developed criteria for determining the acceptability of open water disposal. The enforcement of these criteria has led to the increased use of land or offshore containment areas to deposit these dredged materials.

Various criteria have been used from time to time to determine whether or not dredged bottom sediments are acceptable for open water disposal; however, as with virtually all pollution control criteria, these have been subjected to much controversy. Nevertheless, they have formed the basis for evaluating the pollution potential of dredged materials and have played a major role in deciding which of the alternative disposal schemes is most appropriate; as such, these criteria have had a substantial impact on the economics and feasibility of dredging operations. Although most situations are evaluated on a case-by-case basis with due consideration being given to the volume of dredged material, time of year, method of disposal, etc., the major factors that influence the decision pertain to the physical, chemical, and biological characteristics of the dredged sediments; critical pollution levels (generally in terms of percent concentration) are assigned to each of these characteristics, and these values may not be exceeded. Such criteria are usually different than the effluent quality requirements set by state or regional water quality control boards.

The requirement to avoid open water disposal of polluted dredgings has led to difficulties in many areas because of a lack of practical and economically feasible alternatives. Aware of this situation and realizing the implications thereof, the U. S. Army Corps of Engineers has undertaken several studies to address this problem and is currently involved in a more extensive five-year, 30 million dollar research program that is being directed and administered at the Waterways Experiment Station. As a result of previous investigations, the currently used major alternative to open water disposal is to deposit the dredged sediments within diked enclosures that are located near the dredging operation. Such a procedure has been found to satisfactorily prevent the polluted sediments from reaching the open waters, and, although very costly, it appears generally more feasible than any other method of disposal, except deposition in open waters. Although the desirability of using diked disposal areas is reasonably well established, there is still a need to study the details associated with such operations and to evaluate the potential benefits that might emanate from confined disposal practices.

While the Corps of Engineers acknowledges the need to restrict open water disposal operations, there is simultaneous concern that proper balance and perspective be retained. For example, it has been estimated that about 7,000 acres of new land are needed each year to contain the volume of maintenance dredgings that are currently being confined; furthermore, because of increasing needs and more stringent regulations, this land requirement will probably increase in the future. Since most dredging projects are located in areas where excessive and often conflicting land requirements exist, it is doubtful that society can tolerate the continued use of diked containment areas solely for waste disposal. On the other hand, if suitable disposal facilities are not provided, dredging operations may be suspended with the attendant adverse effects on shipping and commerce. The needs for judicious trade-offs are obvious, and the problem cannot be approached with tunnel vision.

With our increasing need for additional parks, recreational areas, wildlife sanctuaries, etc., dredged materials, if properly handled, may be construed as a resource rather than a waste. However, since the majority of polluted maintenance dredgings are fine-grained materials with high organic contents and high water contents, the effectiveness and economy of associated landfill operations are often hampered by the time-consuming process of dewatering and consolidation. This aspect is very significant because the costs and benefits associated with this method of disposal on a long-term basis will eventually dictate the feasibility of using diked disposal areas. Land in urban areas surrounding most harbors is usually expensive and difficult to locate. Therefore, landfills of sufficiently high quality will play a positive role in forthcoming systems of urban and regional development, but low quality landfills are virtually worthless and a liability to the community. Since most maintenance dredgings are not ideal materials for building landfills, methods must be sought to improve the settlement and strength characteristics of such dredged materials. Although it is possible to isolate without much difficulty the individual problems involved, the solutions are, unfortunately, not so readily available.

NATURE OF RESEARCH PROGRAM

Cognizant of the issues involved, an extensive four-year research program was undertaken to establish a background of quantitative data and a framework of engineering interpretation within which guidance and insight can be provided regarding the use of dredgings for landfill. The engineering characteristics and mechanical behavior of dredged materials from the Great Lakes area in general, and from the Toledo, Ohio, area in particular, have been studied in considerable detail, both in the laboratory and in the field, and the results have been synthesized to yield information whereby the anticipated response of a landfill composed of similar dredged materials can be reasonably well predicted. The experimental program that was undertaken to accomplish this goal is outlined in Section 4. In addition, a portion of this research effort was devoted to a water quality and quantity study to determine the effect of a typical confined area dredging and disposal operation on surrounding environment, and the results of this investigation are summarized in Section 5.

The physical and chemical character of the polluted dredgings studied in this program is reported in Section 6, and the results exert a significant influence on the measuring and interpretations advanced. Sections 7, 8, and 9 summarize the results of field and laboratory test programs to examine the consolidation and compressibility response, permeability and drainage characteristics, and strength behavior, respectively, of dredged materials. In order to assess the relative importance of gravity drainage and evapotranspiration on the dewatering process of a landfill composed of maintenance dredgings and to facilitate the prediction of their time-dependent water content distribution and settlement response, the one-dimensional mathematical model described in Section 10 was developed.

Section 11 presents the results of a study to evaluate the feasibility of stabilizing dredged materials by means of various chemical additives; while some attention was given to economic considerations, the principal thrust of this work is technical. And finally, a synthesis of the most significant conclusions emanating from this study is given in Section 12; although these findings are developed primarily from tests on samples from the Toledo area, it is expected that they will be applicable to describe the response of reasonably similar dredged materials in diked containment areas. Details of these various studies are reported in the following series of individual reports (available through the National Technical Information Service, Springfield, Virginia 22151):

Technical Report No. 1, Engineering Characteristics of Polluted Dredgings, by Raymond J. Krizek, Gabor M. Karadi, and Paul L. Hummel.

Technical Report No. 2, Stabilization of Dredged Materials, by Raymond J. Krizek, Gilbert L. Roderick, and Jau S. Jin.

Technical Report No. 3, Mathematical Model for One-Dimensional Desiccation and Consolidation of Dredged Materials, by Raymond J. Krizek and Manuel Casteleiro.

Technical Report No. 4, Water Quality Study for a Dredgings Disposal Area, by Raymond J. Krizek, Brian J. Gallagher, and Gabor M. Karadi.

Technical Report No. 5, Behavior of Dredged Materials in Diked Containment Areas, by Raymond J. Krizek and Abdelsalam M. Salem.

SECTION 2

CONCLUSIONS

One commonly used alternative to the open water disposal of polluted maintenance dredgings is to place these sediments in diked containment areas to form landfills of marginal value. This study was directed toward evaluating quantitatively the engineering characteristics of dredged materials as they affect their potential usefulness in a landfill. The work was limited to fresh water dredgings from Great Lakes harbors, and most of the effort was centered around four disposal sites in the Toledo (Ohio) harbor; however, the results are considered to be applicable to a wide range of fresh water maintenance dredgings.

The water quality study demonstrated very clearly that the use of a diked containment area as a settling basin serves to effectively remove from the waterways the contaminants associated with polluted maintenance dredgings because these contaminants tend to associate with the solid particles that are retained within the diked enclosure. Furthermore, the quality of the effluent water discharged from the disposal area was similar to that of the ambient river water and slightly better than that of the groundwater. Although the spoil that is retained in the disposal area represents a concentrated source of various pollutants that might leach into the groundwater, this pollution hazard will probably be small in most cases due to the low permeability of the dredged materials, which consist largely of organic silts and clays with medium to high plasticity or inorganic clays with high plasticity.

Based on results from an extensive series of slurry and conventional consolidation tests, the compression index of these dredgings was found to lie between 0.3 and 0.7 and to increase linearly with both water content and liquid limit, and, for all practical purposes, a value of 0.0006 cm^2/sec can be assumed to represent their average coefficient of consolidation. However, experience suggests that the times needed to reach ultimate settlements in the field may be much shorter than those predicted from conventional laboratory consolidation tests.

A mathematical model was developed to simulate the one-dimensional desiccation-consolidation process that takes place in the field, and theoretical predictions of settlements were found to be in good agreement with measured values. The coefficient of permeability, as obtained from conventional consolidation tests and from direct permeability tests, ranged from about 10^{-7} to 10^{-8} cm/sec (0.1 to 0.01 ft/yr) for dredged materials with void ratios on the order of 1 to 2; however; field infiltration tests on materials with comparable void ratios yielded permeability coefficients about three orders of magnitude higher.

The shear strength of hydraulically deposited dredged materials is generally very low due to the inherent nature of the materials and the high water content that is associated with the placement process. As a consequence of consolidation, which was found to progress at a rate of about 4% per year, the shear strength increased at a rate of about 4 kN/m^2 (0.6 psi) per year for a period of one decade.

In summary, the disposal of dredged sediments in diked containment areas does improve the overall quality of the surrounding surface waters, but it is not clear whether the degree of improvement realized is sufficient to justify the considerably higher costs involved. In addition, the low initial shear strength of these high-water-content, organic materials under natural conditions, along with their slow rate of strength increase with time and their associated large volume changes, seriously limit the usefulness of landfills composed of dredged materials. Unless special steps are taken to improve the quality of these materials, their use will be restricted largely to wildlife refuges, parks, recreational areas, parking lots, access roads, and the construction of light buildings with flexible structural joints and flexible floors which would allow several inches of total settlement and a few inches of differential settlement.

SECTION 3

RECOMMENDATIONS

Although this study contributes substantially to our knowledge regarding the quantitative behavior of polluted maintenance dredgings in a landfill, there are still a number of unanswered questions that need to be addressed; many, but not all of these questions are a consequence of the limited nature of this study. Comparable information must be accumulated for dredgings from a salt water environment and from dredging and disposal operations involving other than periodic deposition of materials in a containment area by use of a hopper dredge. Longer-term effects must be investigated for both the mechanical properties of the landfill and the pollution potential of the leachates. Considerable effort is required to better quantify the pollution status of bottom sediment candidates for dredging and the analytical methods that should be employed.

More attention needs to be given to improvements in the internal hydraulic design characteristics of confined disposal areas in order to obtain a more homogeneous distribution of sediments, as well as greater storage capacity and improved effluent quality. A methodology should be developed to allow the containment area to be designed as a solids-liquid separation facility, making optimum use of flocculating agents and effluent filters, if appropriate and cost effective. Despite the traditional characterization of maintenance dredgings as an undesirable waste product, the possibility of beneficial uses (such as strip mine reclamation, creation of wildlife refuges, beach nourishment, and bottom substrate enhancement) should be examined.

There are a number of legal constraints and questions that demand further attention. For example, water quality criteria often impose severe restrictions on the disposal of dredgings, and turbidity standards for the receiving waters are frequently difficult, if not impractical, to meet. A number of federal and state laws concerned with water quality and land use contain expressions of policy that restrict the disposal and potential usefulness of dredged materials, and these should be objectively evaluated. There are a myriad of laws and regulations that describe the types of property that can or cannot be sold or donated and the procedures that are to be followed in either case; these need to be interpreted with regard to the donation or sale of dredged materials.

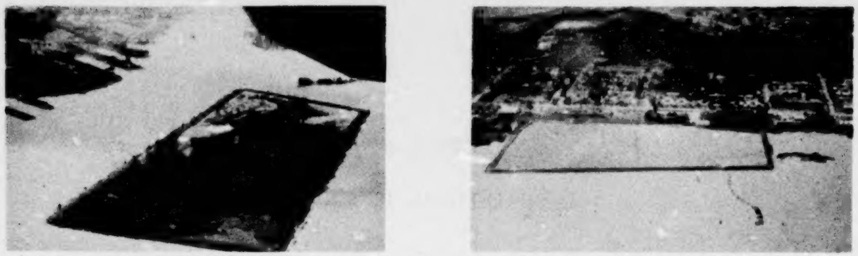
A cost-benefit analysis usually provides the strongest argument (notwithstanding public sentiment) for a given course of action, and further effort must be directed toward assessing the economics associated with dredging and disposal operations on a broad scale. Although improved technology will undoubtedly enhance the economics and environmental acceptability of dredging and disposal operations, the more significant economic factors will probably arise from the nontechnical measures, such as national policy, social acceptance, environmental compatibility, and nature of contractual agreements; for example, a change in the method of payment (based on care and accuracy, rather than primarily on quantity) may substantially affect current practice on many projects.

SECTION 4

EXPERIMENTAL PROGRAM

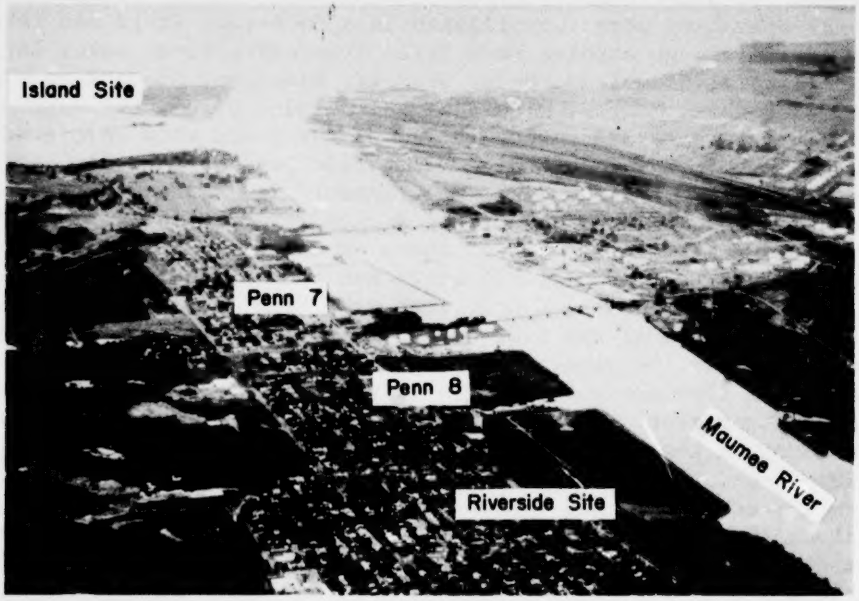
The engineering characteristics of hydraulically placed maintenance dredgings and the water quality effects associated with a typical dredging and disposal operation were investigated in a four-year field and laboratory test program. Although samples were taken from seven Great Lakes harbors (Chicago, Illinois; Cleveland, Ohio; Detroit, Michigan; Green Bay, Wisconsin; Milwaukee, Wisconsin; Monroe, Michigan; and Toledo, Ohio), the vast majority of the laboratory tests and virtually all of the field work were conducted on dredged materials from Toledo, Ohio. The basic reasons for this choice were (a) the availability of a new diked containment area (Penn 7) that would be filled in two years and could therefore be studied from the very beginning of its history and (b) the existence of three other similar disposal sites (Riverside, Penn 8, and the Island) which had been filled during the past ten years or so and could thus be synthesized with Penn 7 to obtain a meaningful historical perspective of the time-dependent behavior of landfills composed of dredged materials. A general layout of these sites is given in Figure 4-1. All four areas are nearly rectangular in plan and enclosed by dikes ranging from about 12 to 20 feet (4 to 6 meters) in height. The Island Site is located at the mouth of the Maumee River at the entrance to the bay; it has dimensions of approximately 3800 feet by 1800 feet (1140 by 540 meters) and covers 150 acres (610,000 square meters). The other three sites are located along the northwest bank of the Maumee River; Riverside, Penn 7, and Penn 8 have respective dimensions of approximately 2200 feet by 700 feet (660 by 210 meters), 1750 feet by 900 feet (530 by 260 meters), and 1200 feet by 900 feet (370 by 280 meters) with areal extents of about 34 acres (140,000 square meters), 31 acres (130,000 square meters), and 25 acres (100,000 square meters), respectively.

During the past ten years about 9 million cubic yards (7 million cubic meters) of bottom sediments were deposited in these four containment areas. As shown in Figure 4-2, approximately 5 million cubic yards (4 million cubic meters) were placed in the Island Site during 1964, 1965, 1967, 1970, 1971, and 1973; 2 million cubic yards (1.5 million cubic meters), in Riverside Site during 1968, 1969, 1970, and 1972; 1 million cubic yards (0.75 million cubic meters), in Penn 7 Site during 1972 and 1973; and 1 million cubic yards (0.75 million cubic meters), in Penn 8 Site during 1966 and 1972. In order to synthesize the time-dependent data from each of these four sites, a time reference or "birthdate" had to be established in each case; for this purpose a time datum for each individual site was selected as the year in which the site was half filled. An examination of Figure 4-2 indicates that the time bases for Penn 7, Penn 8, Riverside, and the Island were 1972, 1966, 1967, and 1968, respectively.

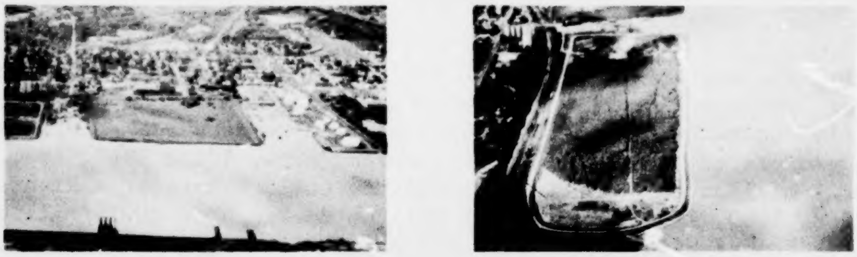


Island Site

Penn 7



Island Site
Penn 7
Penn 8
Maumee River
Riverside Site



Penn 8

Riverside Site

Figure 4-1. Aerial Views of Toledo Disposal Areas

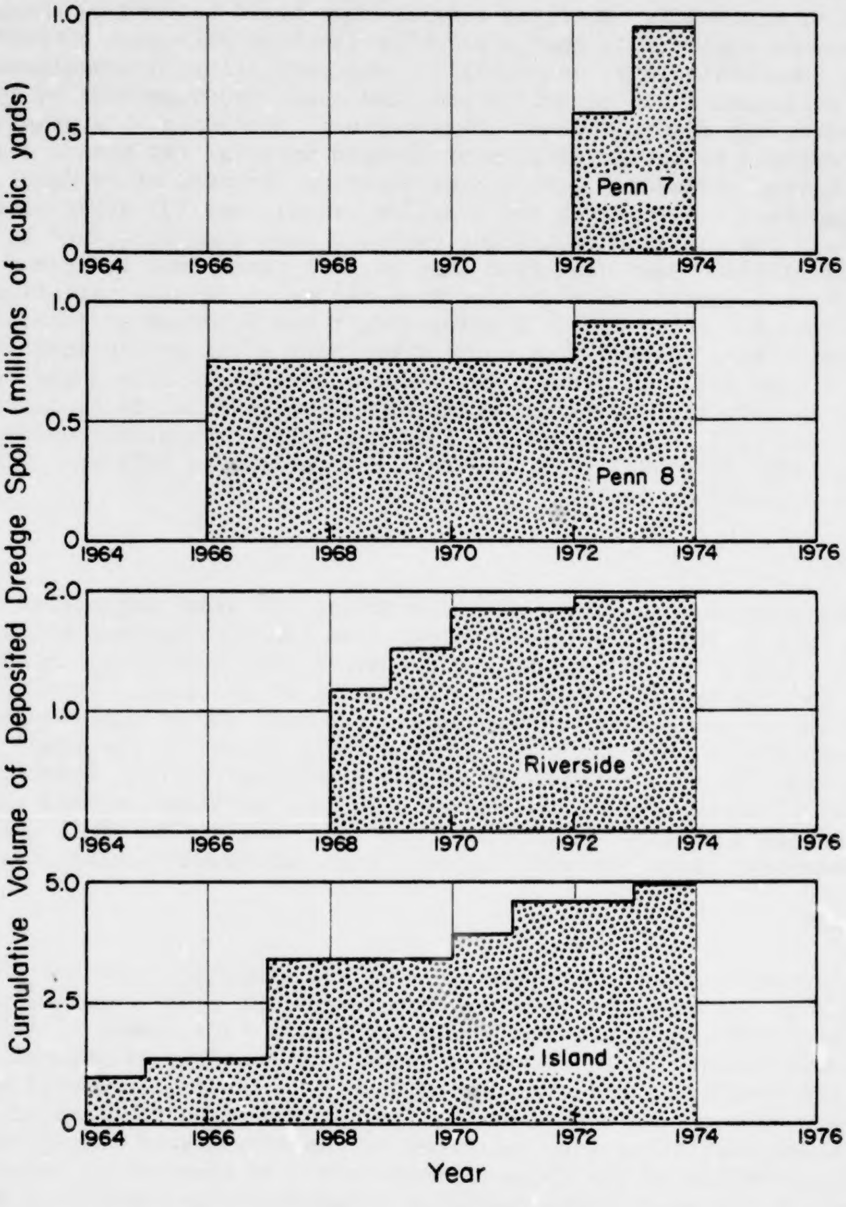


Figure 4-2. Cumulative Volume of Dredgings Deposited in Toledo Containment Areas

SAMPLING

The major objective of the sampling program undertaken in this study was to obtain representative dredging samples that could be used to quantify the time-dependent engineering characteristics (such as pollution potential, strength, compressibility, permeability, susceptibility to stabilization, rates of desiccation and consolidation, and evapotranspiration) of typical dredged materials from the Great Lakes region. Accordingly, a sampling program was devised to obtain samples of dredged material (a) before dredging (ambient bottom sediments), (b) during dredging (hoppers of dredges), (c) during placement (inlet pipes and overflow weirs), and (d) after placement (fill area); the sampling techniques employed have been explained by Hummel and Krizek (1974). Many disturbed samples were taken from locations near the inlet pipe at Riverside Site to determine the particle size variation with distance from the inlet pipe. A major effort was expended to obtain undisturbed piston tube samples from each of the four sites at the locations indicated in Figure 4-3. In particular, samples were taken from three Island locations in 1971 and one Island location (3) in 1973 and 1974, six Riverside locations (1, 4, 5, 6, 7, and 8) in 1971 and three Riverside locations (1, 6, and 8) in 1972, 1973, and 1974, two Penn 8 locations in 1973 and 1974, and nine Penn 7 locations in 1974.

SURVEYING

Field surveys were performed to determine the areal extents of Riverside Site and Penn 7, and periodic elevations were taken to monitor the time-dependent changes in the surface topography of the landfills. In addition, a traverse was run several times along the crest of the Penn 7 dike to ascertain whether or not lateral movements had occurred due to the placement of dredged material within the site. In the early phases of the study seismic (Krizek, Franklin, and Soriano, 1974) and electrical (Giger, Franklin, and Krizek, 1973) field logging techniques were used at Riverside and the Island Site to estimate spatial variations in material characteristics, and variations determined therefrom were compared with subsequent boring logs.

FIELD STUDY

Field vane strengths were measured at all sampling locations shown in Figure 4-3 at the time when samples were taken. At some locations in Penn 7, additional field vane tests were conducted in the late summer of 1974, but no samples were taken. In an effort to assess the possible effects of evaporation on the dewatering and strength buildup of a landfill, several series of small-scale (about 0.25 square meter) field evaporation tests under drained and undrained conditions were performed in the vicinity of Penn 7 and the Toledo Field Office of the Corps of Engineers. In view of the importance of the permeability and drainage characteristics of dredged materials in a landfill, two field infiltration tests were conducted at Riverside Site to supplement an extensive laboratory test program.

A major thrust of this study was to investigate in considerable detail the performance of a typical disposal area, which was selected to be the Penn 7 Site. As this containment area was being filled, an extensive field

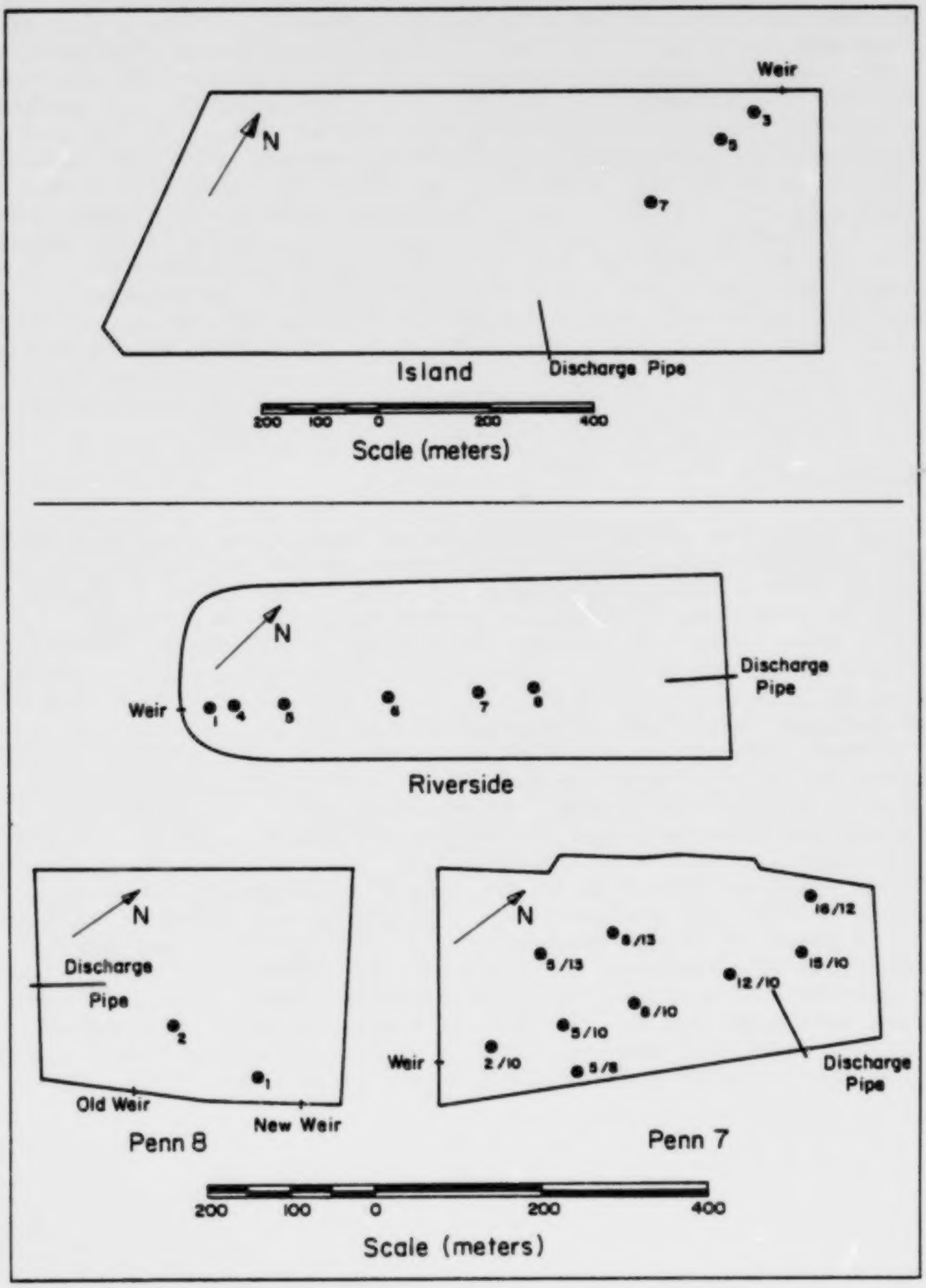

Weir
N
3
5
7
Island
Discharge Pipe
200 100 0 200 400
Scale (meters)
N
Weir
1
4
5
6
7
8
Discharge Pipe
Riverside
N
Discharge Pipe
2
1
Old Weir
New Weir
Penn 8
N
16/12
8/13
5/13
15/10
12/10
8/10
5/10
2/10
5/8
Weir
Discharge Pipe
Penn 7
200 100 0 200 400
Scale (meters)

Figure 4-3. Locations of Field Tests

monitoring program was undertaken to evaluate the effects of such a dredging and disposal operation on the water quality parameters of the environs; primary emphasis was given to the inflow and outflow materials from the containment area, and parameters obtained therefrom were compared with each other and with similar parameters of ambient waters, groundwaters, and samples taken at other stages of the dredging and disposal cycle. In the landfill itself specially designed settlement plate-piezometer units were installed at five locations (2/10, 5/8, 5/10, 5/13, and 15/10 in Figure 4-3) to monitor the time-dependent variations in the settlements and the pore water pressures. A series of field permeability tests was conducted on the foundation soils of the Penn 7 disposal site in order to provide guidance for selecting drainage conditions at the bottom boundary for use in the mathematical model. As mentioned previously, Penn 7 was chosen for this work because it offered an opportunity to study the history of a diked containment area from a time prior to the deposition of any spoil until a time about one year after it was filled. Slurry and groundwater sampling was required for this purpose. Also, an attempt has been made to establish a water budget.

LABORATORY STUDY

Much supporting effort in this research program was directed towards a rather comprehensive laboratory determination of the various engineering characteristics of dredged materials. A large number (several thousand) of chemical analyses were performed to assess the pollution potential of dredged materials under chemically treated and nontreated conditions. Several series of flocculation-sedimentation, sedimentation-leaching, repeated leaching, and evaporation tests were conducted (a) to study the possibility of stabilizing these materials with chemical additives and (b) to evaluate the effects, if any, of such chemicals on the leachates. Numerous index property tests were conducted for classificatory purposes, and several correlations among different properties were established. An extensive series of conventional consolidation tests was performed on undisturbed samples to study both primary and secondary consolidation characteristics, and this consolidation response was supplemented by data from several slurry consolidation tests that were conducted in specially designed slurry consolidometers (Sheeran and Krizek, 1971). A number of direct permeability, gravity drainage, and electroosmosis tests were performed to complement the permeability data that were back-calculated from conventional consolidation tests. Laboratory shear strength determinations made by means of miniature vane, cone, and unconfined compression tests were compared directly with field strength data, and several correlations with index properties were established.

SECTION 5

WATER QUALITY STUDY

This water quality study was conducted at the Penn 7 disposal site in Toledo, Ohio, and consists essentially of two parts. In the first part the input slurry to a disposal site is characterized according to its pollution loading, and the effectiveness of a diked containment area to retain the contaminants in the dredge spoil and to preserve the quality of the water returning to the river is examined by means of an extensive sampling and testing program of influent and effluent materials; also studied is the change in the quality of the groundwater beneath a disposal site. The second part of the study is directed toward evaluating, insofar as possible, the quantitative aspects of the water budget for a typical disposal site.

The diked containment area is regarded as a closed system, and its boundaries are considered to be the four earth sidewalls, the original ground before deposition of any dredgings, and the surface of the water at any given time. Accordingly, the water budget of the diked area can be described in terms of the following variables:

I Influent of slurry pumped from hopper dredge (volume per unit time)
O Outflow discharged over a control weir (volume per unit time)
P Precipitation (volume per unit time)
E Evaporation (volume per unit time)
D Drainage into the groundwater or through the dikes (volume per unit time)
S Storage of water within the diked containment area at any given time (volume)

Hence, at any point in the deposition process the time rate of water storage, $\Delta S/\Delta T$, may be expressed as

$$\Delta S/\Delta T = (I + P) - (O + E + D) \quad . \tag{5-1}$$

However, only four of the six budget variables are known with any degree of accuracy. The outflow quantity, O, was measured and recorded by a flow measuring system installed at the discharge weir. Precipitation and evaporation, P and E, were monitored by a recording rain gauge and a recording evaporimeter installed nearby at the Toledo Field Office of the Corps of Engineers. The quantity of water stored, S, and time rate of change of water stored, $\Delta S/\Delta T$, were obtained from measurements of the water level, which was incrementally controlled by changing the height of the discharge weir. It was planned to obtain the inflow quantity, I, from Corps of Engineers records of pumping operations, but it turned out that these records do not reflect the quantities of flush water used to clean the hopper dredge and pipeline before and after pumping operations; consequently, I is not known with any degree of certainty. The sixth variable, D, was not measured. (This variable was originally intended to play the role of the balance term in the water budget.) Although it is possible that some slight runoff could enter the diked containment area, surface runoff was assumed to be negligible.

This study spanned the period from August 20 to December 20, 1972, during which time dredgings were pumped almost continuously (about 8 loads per day, except on Sundays) into the Penn 7 area. However, it was not until October 19, 1972, that the water level in the disposal site reached the point where effluent began to flow over the weir; then, on November 13, 1972, the flow meter malfunctioned. Although data for the water quality study were accumulated over virtually the entire four-month period, the collection of water quantity data to establish the water budget was limited to a 26-day period for all practical purposes.

WATER QUALITY EVALUATION

A sampling program was undertaken to characterize, insofar as reasonably possible, the quality of the dredged materials and associated waters at various stages during the dredging and disposal cycle. Specifically included in this characterization are samples of (a) bottom sediments, (b) water from the overflow of the hopper dredge, (c) material from the bin of the hopper dredge, (d) slurry from the inflow pipe to the disposal area, (e) water from the overflow weir of the disposal area, (f) river water, and (g) groundwater, but emphasis was given to the influent and effluent samples from the inflow pipe and overflow weir. The details of this study have been presented by Krizek, Gallagher, and Karadi (1974), and only a brief summary of the results is included herein.

Sampling Program

Since dredgings were pumped into Penn 7 during 107 days over a 123-day period at a rate of approximately 8 loads per day, there were about 850 individual inputs of varying quality and quantity. Ideally, the influent and effluent materials should have been sampled several times during each pumping operation since the nature of the dredgings varied considerably. However, this would have posed an impossible task of sampling and analysis, and a random sampling approach was therefore pursued. One-gallon (3.8-liter) samples were normally collected, packed in ice chests, and transported to the laboratory, where they were stored at approximately 4°C until tested. Special handling was given to the samples to be subjected to bacteriological tests, and such tests were conducted within 24 hours.

Special efforts were made to evaluate the adequacy of the sampling procedures utilized and the statistical significance of the resulting data. In certain cases samples were taken (a) simultaneously from different points in the slurry jet emerging from the inflow pipe, (b) from the same load at five-minute intervals, (c) from each load in any given day, and (d) from two or three loads every day for four or five consecutive days. Variability tests on these groups of samples were performed to assess the adequacy of a sampling program wherein replicate samples of slurry inflow were collected randomly once or twice a week; however, no samples were taken during the extreme beginning or end of a pumping cycle since such periods would likely be dominated by flush water and thereby yield grossly unrepresentative samples. Variations in samples from the overflow weir were relatively small compared to variations in slurry samples, and fewer samples were therefore taken. Initial groundwater samples were taken prior to the deposition of any dredgings in the area, and follow-up sets of samples were taken about one year after dredging disposal had commence and after the site was filled. An extremely limited number of samples were obtained during each of the other stages of the dredging and disposal operation, so the results must be assessed accordingly.

Laboratory Analyses

The influent into the diked disposal area was expected to have a high solids content consisting of silt, clay, and organic matter. In addition, high levels of phosphorus and nitrogen were expected since the sediments originate in agricultural areas. Many trace metals and some heavy metals and other toxic substances were anticipated, and, due to the industrial nature of the local surroundings, it was likely that oil, grease, and other persistent organics would be found. Although it was expected that most of the solids and insoluble substances would be retained in the diked area, it is probable that all of these contaminants would be found in trace quantities in the effluent with the more soluble substances in higher concentrations. Accordingly, the fairly comprehensive set of analyses outlined below was undertaken to quantitatively evaluate these aspects of the problem. In addition, some bacteriological tests were performed, and a gas chromatographic analysis was conducted on the solids and water portions of one sample to determine the presence of chlorinated organic compounds.

General Water Quality Parameters

Total Solids
Dissolved Nonvolatile Solids
Suspended Nonvolatile Solids
Hydrogen Ion Concentration (pH)
Total Silica

Nutrients

Total Nitrogen
Ammonia Nitrogen
Nitrate Nitrogen
Nitrite Nitrogen
Total Phosphate
Soluble Phosphate

Organics

Biochemical Oxygen Demand (BOD)
Chemical Oxygen Demand (COD)
Total Volatile Solids
Suspended Volatile Solids
Dissolved Volatile Solids
Oil and Grease

Metals

Cadmium
Calcium
Copper
Iron
Lead
Manganese
Potassium
Sodium
Zinc

Sample Variability

During this sampling program, several variability tests were conducted on the influent materials by sampling periodically during some particular phase of the disposal operation. In one series of tests samples were taken at five-minute intervals after pumping started until it was almost completed, and it was found that the concentrations of several constituents in the sample varied considerably, but irregularly, with a slightly decreasing trend as pumping continued. A similar series of variability tests was performed on samples taken intermittently over a period of 14 hours, but again no clearly predictable patterns were detected. Based on the results of these tests, it was decided that replicate samples collected randomly (except to avoid the extreme starting or ending periods of a pumpout cycle) once or twice a week would yield representative samples for the determination of influent quality.

Comparison of Influent-Effluent Quality

Detailed data from the chemical analyses on the influent slurry samples and effluent water samples were first averaged on a daily basis (that is, the measured values for all samples taken in any given day were averaged); then, these daily averages were averaged over the duration of the field test program, and the overall results are summarized in Table 5-1. It can readily be seen that the diked containment area serves effectively to retain a substantial portion of virtually all pollutants. Of the sixteen parameters listed in Table 5-1, the concentrations of ten were reduced by well over 95%, and five were reduced by values ranging from 45% to 90%; nitrate nitrogen showed a more than tenfold increase, but this was not unexpected. If viewed in terms of the pollution criteria given in Table 5-2, the average values (when converted to a dry weight basis) of volatile solids, COD, lead, and zinc exceed the specified limiting concentrations, thereby ascertaining that these dredgings are "polluted"; since no measurements of total Kjeldahl nitrogen, oil and grease, or mercury were made, definite evaluations regarding their role as "pollution parameters" cannot be advanced.

Fate of Pollutants during Dredging and Disposal Cycle

Table 5-3 places the influent-effluent comparisons described above in the broader context of the overall dredging and disposal cycle. In addition to the extensive sampling program undertaken for influent and effluent samples, a limited number of samples were taken from the harbor bottom before dredging, from the hopper of the dredge and from the hopper overflow during the dredging operation, from the ambient river water away from the disposal site, and from the groundwater in the vicinity of the disposal site. Within the framework of these data (first averaged on a daily basis, and then an average of the daily averages), the following conclusions may be advanced:

1. The concentrations of pollutants are very high in the bottom sediments, the materials in the hopper bin, and the water that overflows the hopper bins as they become filled.

2. Although still quite high, the concentrations of pollutants in the slurry deposited in the containment area are reduced somewhat by the addition of ambient river water, which acts as a carrier to pump the dredgings into the diked enclosure; however, the contaminants appear to reflect agricultural deposits rather than industrial or sewage wastes.

Table 5-1. Comparison of Average Influent-Effluent Concentrations

Parameter	Units	Concentration		Percent Increase (+) or Decrease (-)
		Influent Penn 7	Effluent Penn 7	
Total Solids	%	14.9	0.043	-99.7
Total Silica	%	11.5	0.014	-99.9
Chemical Oxygen Demand	mg/ℓ	15,000	135	-99.1
Biological Oxygen Demand	mg/ℓ	334	5.3	-98.4
Total Phosphate	ppm	344	4.5	-98.7
Nitrite Nitrogen	ppm	0.045	0.010	-77.8
Nitrate Nitrogen	ppm	0.7	8.0	+1145
Cadmium	ppm	0.66	0.24	-63.5
Calcium	ppm	4000	100	-97.5
Copper	ppm	7.1	3.9	-45.0
Iron	ppm	3000	.5.6	-99.8
Lead	ppm	10.3	5.7	-45.0
Manganese	ppm	63	2.1	-96.7
Potassium	ppm	525	6.5	-98.8
Sodium	ppm	120	15	-87.5
Zinc	ppm	17	0.7	-95.9

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Table 5-2. Guidelines for Limiting Concentrations of Various Pollutants in Bottom Sediments

Penn 7

Parameter	Percent Concentration (Dry Weight Basis)
Volatile Solids	6.0
Chemical Oxygen Demand (COD)	5.0
Total Kjeldahl Nitrogen	0.10
Oil and Grease	0.15
Mercury	0.0001
Lead	0.005
Zinc	0.005

Table 5-3. Average Values of Chemical Parameters at Various Stages of Dredging and Disposal Cycle

Penn 7

Chemical Parameter	Units	Average Value						
		Bottom Sediments	Hopper Overflow	Hopper Bin	Slurry Inflow	Dike Overflow	River Water	Ground Water
Total Solids	%	33.031	19.106	43.508	14.890	0.046	0.023	0.228
Total Nonvolatile Solids	%	31.858	18.459	42.072	13.909	0.036	0.019	0.179
Total Volatile Solids	%	1.173	0.647	1.437	1.116	0.012	0.004	0.073
Nonvolatile Suspended Solids	%	31.832	18.431	42.044	13.858		0.019	0.122
Volatile Suspended Solids	%	1.159	0.631	1.425	1.099		0.004	0.032
Nonvolatile Dissolved Solids	%	0.026	0.028	0.028	0.051			0.057
Volatile Dissolved Solids	%	0.014	0.016	0.012	0.017			0.041
Total Silica	%	26.203	14.294	35.371	11.50	0.014	0.012	0.079
Chemical Oxygen Demand	mg/l	31,100			15,000	135	122	187
Biochemical Oxygen Demand	mg/l		380		334	5.3	2	4.1
Total Nitrogen	ppm				135			13.5
Ammonia Nitrogen	ppm				87			13.5
Nitrite Nitrogen	ppm	0.038	0.016	0.013	0.045	0.01	0.01	0.026
Nitrate Nitrogen	ppm	0.402	0.176	0.142	0.694	8.03	7.8	11.1
Total Phosphate	ppm	632		476	344	4.5	3.9	7.4
Soluble Phosphate	ppm	0.112		0.065	0.146			
Cadmium	ppm	1.57	1.85	1.39	0.66	0.24	0.30	0.33
Calcium	ppm	7,400	6,600	6,600	4,000	101	75	273
Copper	ppm	8.4	9.2	8.8	7.1	3.9	7.5	6.2
Iron	ppm	4,400	5,700	3,600	3,000	5.5	7.3	65.5
Lead	ppm	14.2	11.5	15.6	10.2	5.7	6.0	6.7
Manganese	ppm	115.4	92.3	137.3	62.8	2.1	3.0	3.2
Potassium	ppm	295	335	240	525	6.5	9.9	26.4
Sodium	ppm	121.8	187.5	164.3	121.2	15.1	10.2	38.1
Zinc	ppm	33.9	29.4	39.8	17.1	0.7	0.8	1.12
Oil and Grease	%				0.19			
pH		6.8	6.9	7.0	6.9	6.7	6.8	6.7

3. With the exception of nitrate nitrogen, a marked reduction in pollutant concentrations occurs before the effluent water is discharged over the weir back into the river, and the quality of the effluent water is similar to that of the river water.

4. The quality of the groundwater is slightly worse than that of either the river water or the effluent water.

Pesticides

Gas chromatograph analyses were conducted on the solid and supernatant phases of one slurry sample to check for the presence of pesticide materials. Based on this very limited amount of data, it appears that significant amounts of chlorinated organic compounds are present in dredged sediments or suspended solids, but, due to their insolubility, only a trace of these compounds was detected in the supernatant water. A similar conclusion was obtained from a much more comprehensive investigation reported by Krizek, Karadi, and Hummel (1973).

Bacteriological Analyses

Samples taken from the slurry influent, dike overflow, underlying groundwater, and a few other sources were tested before, during, and after the disposal of dredgings in the Penn 7 area to determine the presence of bacteriological organisms, and the detailed results are summarized in Table 5-4. The total and fecal coliform tests have been used traditionally as indicators of polluted water which could be a health hazard; the presence of fecal coliforms in significant numbers suggests that fecal matter from animals or human beings has contaminated the water and that other pathogenic bacteria may be present.

Although the interpretation of such tests is very difficult due to the many variables that can affect the results, the limited data given in Table 5-4 suggest that the slurry influent is extremely polluted from a bacteriological point of view; fecal coliforms are in the tens of thousands of organisms per 100 mℓ, and total coliforms typically range from tens of thousands to hundreds of thousands of organisms per 100 mℓ. The effluent water from the diked enclosure, as well as the water from the Maumee River, is quite polluted at some times but relatively unpolluted at other times. To place the test data in perspective, the standards for most states require zero coliforms for drinking water quality, but they allow as high as 1000 organisms per 100 mℓ for contact sports (such as swimming) and up to 5000 organisms per 100 mℓ for noncontact sports (such as boating). The State of Ohio standards for lakes and streams require that the average of at least five samples taken within 30 days does not exceed 200 fecal coliforms per 100 mℓ and that not more than 10% of the samples exceed 400 organisms per 100 mℓ. Although many more samples would have to be taken and tested before any final judgment could be made (as the numbers of bacteriological organisms can change rapidly due to varying environmental conditions), it appears that the effluent water from the Penn 7 containment area resembles the general quality of the water in the Maumee River.

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Table 5-4. Summary of Data from Bacteriological Analyses

Sample Location and Time	Total Coliforms (organisms per 100 mℓ)			Fecal Coliforms (organisms per 100 mℓ)		
	Number of Samples	Range	Mean	Number of Samples	Range	Mean
Groundwater from Wells (0 to 10 feet) August 2, 1972	2	24,000 to 32,000	28,000	2	160 to 580	370
Groundwater from Wells (10 to 20 feet) August 2, 1972	4	40 to 120,000	300[a]	4	< 1 to 5,700	< 1[b]
Groundwater from Wells (0 to 10 feet) August 1, 1973	6	100 to 55,000	19,000	6	15 to 2,400	1,270
Groundwater from Wells (10 to 20 feet) August 1, 1973	2	11,000 to 46,000	28,500	2	9,300 to 11,000	10,150
Groundwater from Wells (0 to 10 feet) August 22, 1974	3	30 to 700	260			
Groundwater from Wells (0 to 10 feet) February 6, 1975	4	0 to 700	400			
Influent Slurry August 25, 1972	5	600,000 to 2,000,000	680,000[c]	5	23,000 to 60,000	44,000
Influent Slurry August 1, 1973	3	24,000 to 165,000	24,000[d]	3	9,300 to 69,000	9,300[e]
Stagnant Mud from Disposal Area August 1, 1973	1		1,125,000	1		1,125,000
Stagnant Water from Disposal Area August 1, 1973	1		210,000	1		270
Water from Overflow Weir August 1, 1973	1		70,000	1		330
Water from Overflow Weir August 22, 1974	1		100			
Water from Maumee River August 1, 1973	1		83,000	1		1,200
Water from Maumee River August 22, 1974	1		15			
Water from Maumee River February 6, 1975	1		0			
Tap Water from C. E. Field Office August 22, 1974 and February 6, 1975	2		0			
Tap Water from Well of Local Motel August 22, 1974 and February 6, 1975	2		0			

Notes:

a Mean value excludes one sample with a value of 120,000

b Mean value excludes one sample with a value of 5,700

c Mean value excludes one sample with a value of 2,000,000

d Mean value excludes one sample with a value of 165,000

e Mean value excludes one sample with a value of 69,000

The situation regarding the groundwater is very difficult to assess due to the wide variation of test results. Although some localized areas appear reasonably unpolluted, others appear quite highly polluted. The data indicate that some degree of pollution existed before any dredged spoil was placed in the diked enclosure; this was probably caused by the presence of stagnant surface waters. It was observed that many wild animals, such as pheasants, ducks, rabbits, and rats, used the partially water-filled dike enclosure as a habitat, and this could account for the presence of coliforms in relatively high numbers. However, these data do not suggest that the disposal of dredgings in the Penn 7 area has adversely affected the quality of the groundwater from a bacteriological point of view during the time period of this study. The stagnant mud and water within the diked area are extremely polluted, and the goundwater may become polluted with time due to leaching of the deposited dredged materials.

WATER BUDGET

Included in this section are brief descriptions of the techniques used to establish quantitative values for the various components of the water budget. Detailed data have been presented by Krizek, Gallagher, and Karadi (1974), and only summaries of the results are given here.

Effluent

A recording flow meter was installed at the overflow weir to record the quantity of effluent that exited the system over the weir. The outflow quantity was calculated from the recorded crest height in conjunction with a rectangular weir arrangement. The system was installed on October 3, 1972, before the dike had filled to the overflow level, and it began recording on October 19, 1972. The recording system operated satisfactorily for the first 24 days, but it malfunctioned during the last 30 days while the disposal area was being filled. However, usable data obtained during the period of operation provided considerable insight into the water quantity budget. The quantity of water that left the disposal area via the calibrated overflow weir between October 19 (at which time the water first began to flow over the weir) and November 13 (about which time the probe became inoperable due to vandalism) was recorded. An average of these data taken over the 26-day test period indicates that about 425,000 cubic feet (12,000 cubic meters) of water exited the disposal area each day via the overflow weir.

Seepage

Undetermined amounts of water may have seeped into the underlying foundation soils or through the earthen dikes during the course of this test program. Although there was no reasonable way to measure this quantity, it is believed to be small due to the low permeability of the dredged materials (Krizek and Casteleiro, 1974).

Influent

As stated previously, it was intended to obtain the quantity of influent water and slurry pumped into the disposal area from Corps of Engineers records, but available data render impossible the task of determining this quantity with any degree of accuracy. Nevertheless, inflow quantities deduced from the information available are reasonably consistent with measured outflow quantities and the nature of the pumping operation.

Precipitation and Evaporation

A recording rain gauge and a recording evaporimeter were installed at the Toledo Field Office of the Corps of Engineers, and daily records of the precipitation, evaporation, net input, and accumulative input between August 20 and December 20, 1972, were obtained. The net accumulative input over the entire test period was recorded as 8.64 inches (22.0 centimeters) which, when distributed over an area of 1.34 million square feet (0.125 million square meters), represents a total volume input to the disposal area of about 970,000 cubic feet (27,000 cubic meters) or almost 8,000 cubic feet (220 cubic meters) per day on the average. Of particular concern to this study is the 26-day period from October 19 to November 13, 1972, during which time the major part of the usable data was accumulated. Since there was a net accumulative input of 2.60 inches (6.6 centimeters) during this period, the total volume input would amount to about 290,000 cubic feet (8,000 cubic meters) and the daily input was almost 11,000 cubic feet (300 cubic meters). These daily volumes represent about 2% of the daily quantity of water that exited the disposal area via the overflow weir; consequently, its role in modifying the quality of the waters comprising the water budget can be reasonably neglected.

Synthesis

Although the water budget cannot be balanced with any degree of accuracy due to a combination of incomplete and inadequate data, the proper orders of magnitude can be reasonably well established from an overall evaluation of the available data. The quantity of effluent from the area was determined with a fair degree of confidence to average about 425,000 cubic feet (12,000 cubic meters) per day for the first 26 days during which water overflowed the weir, and the quantity of influent substantiates this measurement in a general way. Since the measured net volume of precipitation and evaporation represents less than 2% of the effluent quantity, it can be neglected, especially in the water quality analyses. The undetermined quantity of seepage into the underlying foundation soils is probably small due to the low permeability of both the dredgings and the upper strata of the original ground. Runoff into the containment area is almost certainly negligible due to the presence of a surrounding dike.

The total amounts of dredged material placed in Penn 7 during the 1972 and 1973 dredging seasons were about 570,000 and 350,000 cubic yards (440,000 and 270,000 cubic meters), respectively, in terms of bin-measure volume. When multiplied by 0.65 to convert bin-measure volumes to disposal-site volumes (Krizek and Giger, 1974), these materials occupy about 370,000 and 230,001 cubic yards (280,000 and 180,000 cubic meters), respectively. Assuming an in-place dry density of 50 pounds per cubic foot (8 kN/m^3) and a value of 2.70 for the specific gravity of solids, the actual solids may be determined to occupy only about 30% of the bulk volume. Hence, when viewed in context of the overall volumes of solids and water pumped into a disposal area, the net volume of the solid particles represents only a small portion of the total volume.

SUMMARY

A four-month water quality study was conducted at the Penn 7 disposal site in Toledo, Ohio, and an assessment of the fate of pollutants during the dredging disposal cycle was made. In general, it was found that (a) the concept of using a diked containment area as a settling basin to retain the solids in dredged materials does effectively improve the water quality of the mixtures that pass through it; many of the contaminants apparently associate with the solid particles, thereby settling out of suspension with the solids and reducing significantly the concentrations of polluting materials; (b) the quality of the effluent that was discharged from the disposal area is similar to that of the ambient river water and slightly better than that of the groundwater; and (c) the retained spoil in the diked enclosure represents a concentrated source of various pollutants that may leach into the groundwater as time passes, thereby reducing to some extent the advantage gained by placing polluted dredged materials in confined disposal areas. Although considerable efforts were expended to monitor the various components of the water budget, limited success was achieved because it was impossible to obtain accurate information on the quantity of influent materials and the seepage losses could not be measured.

SECTION 6

MATERIAL CHARACTERIZATION

The characterization of dredged materials constitutes an essential part of this study because (a) it provides the background for subsequent correlations among index properties and engineering properties and (b) it establishes the feasibility of combining the data from all four Toledo disposal sites to form one hypothetical site with a deposition history of about ten years. Therefore, a number of conventional criteria employed in the field of soil mechanics have been used to characterize many dredging samples, most of which were taken from the four Toledo sites. In particular, the Atterberg Limits, water content, dry density, grain size parameters, organic content, mineralogy, and chemical composition were found although all parameters were not determined for all samples. Index properties were determined according to standard procedures (Lambe, 1951) except for a minor modification in some of the hydrometer analyses (where the dispersing agent was omitted to more realistically reflect the actual conditions of sedimentation in a disposal area). The methods of testing for organic content, chemical constituents, and mineralogical composition have been explained by Krizek, Karadi, and Hummel (1973). Index property tests were conducted on materials sampled at three different consistencies; these were 6 samples of a high-water-content slurry (solids content of about 15% by weight), 8 samples with a mud-like consistency (solids content larger than 25% by weight), and 120 samples (23 from the Island, 49 from Riverside, 31 from Penn 7, and 17 from Penn 8) of solid material that was capable of maintaining a given shape. In addition, over 3000 chemical analyses were performed to determine the chemical constituents of many of these samples, as well as a large number of water samples.

RESULTS

The general results of these characterization tests are presented in the following paragraphs and in Table 6-1 and Figure 6-1, which summarize grain size characteristics and Atterberg Limit relationships, respectively.

Natural Water Content and Dry Unit Weight

Water contents ranged from 45% to 70%, 47% to 73%, and 42% to 68% for samples obtained from Riverside in the summers of 1972, 1973, and 1974, respectively; from 51% to 74% and 52% to 70% for Penn 8 samples and from 54% to 55% and 43% to 78% for Island samples taken in the summers of 1973 and 1974, respectively; and from 67% to 98% for Penn 7 samples taken in the summer of 1974. Dry unit weights ranged from 910 kg/m^3 to 1090 kg/m^3, 860 kg/m^3 to 1140 kg/m^3, and 880 kg/m^3 to 1125 kg/m^3 for samples obtained from

Riverside Site in 1972, 1973, and 1974, respectively; from 890 kg/m^3 to 1070 kg/m^3 and 850 kg/m^3 to 1110 kg/m^3 for Penn 8 samples and from 980 kg/m^3 to 1120 kg/m^3 and 840 kg/m^3 to 1240 kg/m^3 for Island samples taken in 1973 and 1974, respectively; and from 740 kg/m^3 to 980 kg/m^3 for Penn 7 samples taken in 1974. These values provide an appreciation for the water contents and dry unit weights of dredgings that are left dormant in diked areas for different periods of time. Some of the variations in the water contents and dry unit weights of samples from different sites can be explained by variations in drainage conditions, thickness of layer, relative surface levels of the different sites compared to that of Lake Erie, and the partial flooding that occurred in some sites due to certain abnormally high water levels of Lake Erie and the Maumee River.

Table 6-1. Summary of Grain Size Analyses

Site	Percent Clay	Percent Silt	Percent Sand	Mean Size D_{50} (mm)	Effective Size D_{10} (mm)	Uniformity Coefficient $U=D_{60}/D_{10}$	Number of Samples
Island	31	50	19	0.0098	0.0026	6.1	5
Penn 8	37	48	15	0.0073	0.0022	5.5	12
Riverside	40	46	14	0.0082	0.0019	5.9	26
Penn 7	36	47	17	0.0075	0.0020	7.0	23
Overall Average	37	47	16	0.0079	0.0021	6.2	66

Variation of Liquid Limit and Plastic Limit with Clay Content

The liquid and plastic limits are plotted in Figure 6-1 versus percent clay for 65 dredging samples. Four different symbols are used in these plots to distinguish the four different field sites, but the years during which the samples were obtained are not identified. In general, no patterns can be identified to distinguish one site from another, and the data from the different sites appear to be randomly interspersed, thereby suggesting that the limits can be treated as representative of samples from one source. The liquid limit, w_L, varies between about 50% and 100% whereas the clay content ranges from about 20% to 50%, and, as shown in Figure 6-1, the relationship between the two can be expressed as

$$w_L = 1.3\ (\%\ \text{clay} + 20) \quad , \qquad (6\text{-}1)$$

in which the variables are expressed in percent. The scatter around the line represented by Equation (6-1) is about ±15% and is attributed to the variations in the materials. The plastic limit, w_P, for the same samples is plotted in Figure 6-1 versus percent clay, but no definite trend can be discerned.

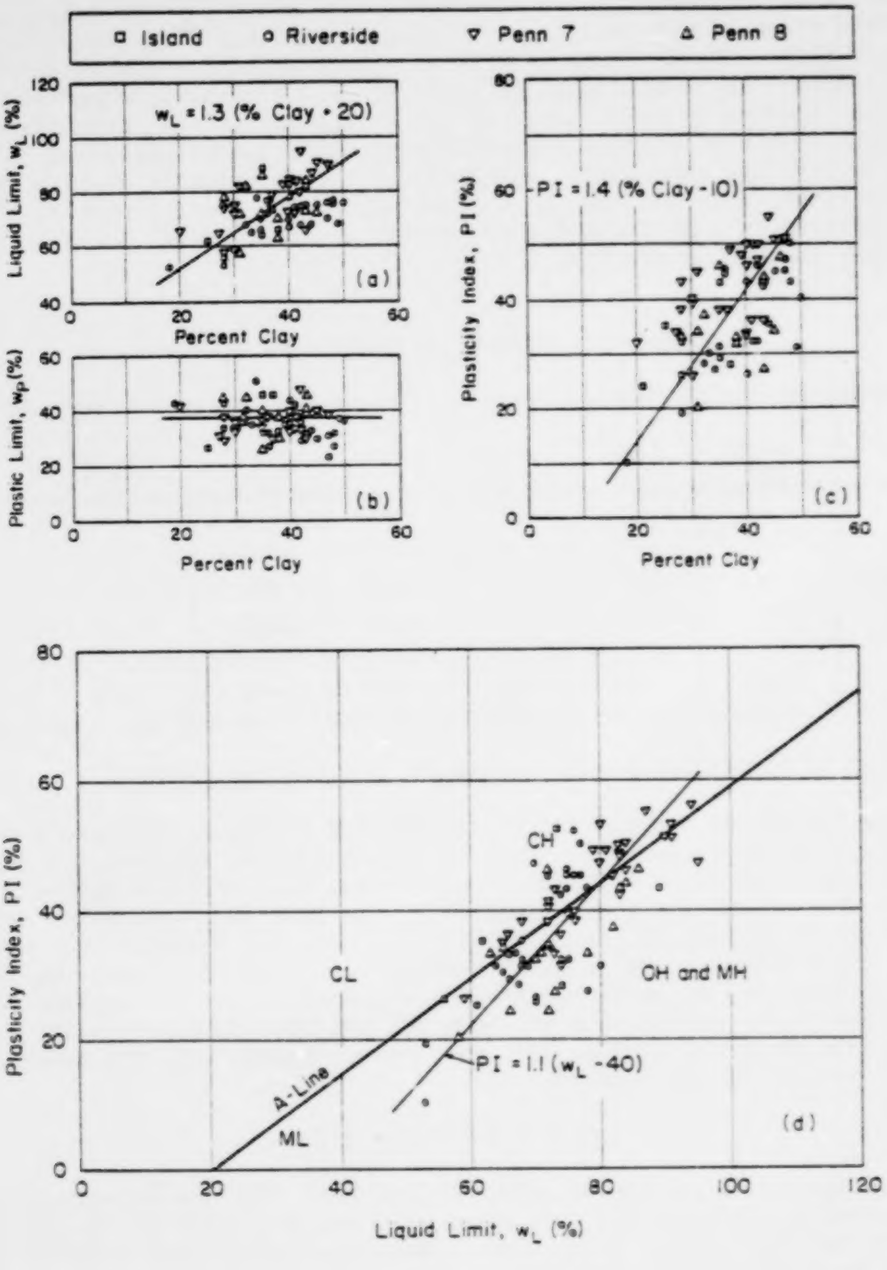

Figure 6-1. Plasticity Relationships

Variation of Plasticity Index with Percent Clay

Of interest in any soil classification system is the relationship between plasticity index, PI, and clay content; the ratio of the plasticity index to the percent clay has been used as the basis for defining the activity of clays (Skempton, 1953). Based on the plot in Figure 6-1 for 65 dredging samples, a straight line relationship showing an increase in plasticity index with an increase in percent clay was found, but the most representative line did not pass through the origin. The empirical equation best representing this relationship can be written as

$$PI = 1.4\ (\%\ \text{clay} - 10) \quad , \qquad (6\text{-}2)$$

where the variables are expressed in percent. Hence, the average value of the activity for these dredged materials is found to be about 1.4.

Relationship between Plasticity Index and Liquid Limit

The plasticity index, PI, is plotted in Figure 6-1 versus the liquid limit, w_L, on the Casagrande (1948) plasticity chart for 83 samples of dredgings (6 from the Island, 16 from Penn 8, 30 from Riverside, and 31 from Penn 7). All data points lie essentially within a PI range from about 20% to slightly more than 50%, and according to the plasticity chart, these dredgings can be classified as a mixture of organic clays of medium to high compressibility and inorganic clays of high plasticity, with slightly more than one half of the samples falling into the former category. The relationship between plasticity index and liquid limit can be expressed as

$$PI = 1.1\ (w_L - 40) \quad . \qquad (6\text{-}3)$$

Variation of Limits and Plasticity Index with Activity

Since the nature of the clay fraction may vary considerably in dredged materials, variations in the Atterberg Limits and plasticity index with changes in activity were investigated. The liquid limit was found to increase linearly with an increase in the activity, A, and the relationship can be written as

$$w_L = 25\ (A + 1.6) \quad . \qquad (6\text{-}4)$$

The plastic limit was observed to have no definite correlation with the activity, and a nonlinear increase of plasticity index was found to occur with an increase in activity. The rate of increase of the plasticity index is high at low values of activity and decreases gradually as the latter increases.

Particle Size Characteristics

The results of particle size distribution curves for 66 samples from the four different sites are summarized in Table 6-1. The average percentages of sand, silt, and clay fractions for the materials in each of the four sites are essentially the same, with the individual components being proportioned on approximately a 1:3:2 basis. The average values of the mean particle size, D_{50}, and the effective particle size, D_{10}, are practically the same for the materials in each of the different sites, with overall averages of 0.0079 mm and 0.0021 mm, respectively. The individual average values for the coefficient of uniformity, D_{60}/D_{10}, vary between 5.5 and 7.0 with an overall average of 6.2.

Organic Matter

Wet combustion (organic carbon) and dry combustion (ignition loss) techniques were used to determine the organic content of these dredgings. Except for a few instances, the organic carbon of the samples tested was found to be on the order of 2% to 4%. If it is accepted that organic matter consists of about 50% organic carbon, the organic matter content for most of the samples will vary from 4% to 8%. It was noticed that the samples with high organic contents exhibited a strong oily odor, and the presence of hydrocarbons may account for such high organic carbon contents. An attempt was made to correlate limit test data with the organic carbon content and the ignition loss, but no success was attained. Although the limit values generally increase with increasing values of organic carbon content or ignition loss, the indicated relationships were not well defined; this is probably due in large part to the effects of other variables, such as gradation, precentage of fines, clay mineralogy, and type of organic material. Furthermore, since the degree of decomposition of the organic matter in the dredgings is generally very high, the existing organic compounds have probably reached a chemically stable condition and do not impart to the dredged materials the same type of behavior as organic matter with a low degree of humification, such as that often found in organic soils.

Chemistry and Mineralogy

The results of an extensive experimental program to analyze the chemical composition of dredged materials has been reported by Krizek, Karadi, and Hummel (1973) and Krizek, Gallagher, and Karadi (1974). In general, virtually all of the dredgings tested would be classified as polluted. The degree of pollution varied considerably from harbor to harbor, from sample to sample within a harbor, and in the intensity of the various pollutants for a particular sample. The chemical composition of the water was very consistent with that expected at particular locations. For example, where sewage was emitted, the dissolved oxygen was low and the biological oxygen demand and nitrogen content were high; this was also true for bottom sediments. However, the chemical oxygen demand depended not only on organic compounds, but also on other materials (such as the nitrite and sulfide anions and the mercurous, cuprous, and ferrous cations) that are found in high concentrations in these dredgings. No definitive relationships could be established between the chemical composition of a sample and its engineering behavior, nor can any general conclusions be advanced regarding the chemical nature of maintenance dredgings since the chemical components of a sample are so highly dependent on the localized environment from which it was taken. Mineralogical analyses on seven different dredgings indicated the presence of substantial amounts of common clay minerals, such as illite and kaolinite. This finding is consistent with findings reported by other agencies (for example, Philadelphia District Corps of Engineers, 1969).

SUMMARY

Samples of dredged materials taken from the four sites at Toledo, Ohio, were found to be essentially the same, thereby allowing data from all four sites to be synthesized and treated as representative of one large site spanning a time period of nearly a decade. The liquid limit and plasticity index were found to exhibit approximately linear relationships with the clay content, but no correlation could be found between the plastic limit and the percent clay. Particle size analyses indicated that sand, silt, and clay fractions exist in approximate proportions of 1:3:2. Virtually all of these dredged materials can be classified as a mixture of organic silts and clays of medium to high plasticity (OH) and inorganic clays of high plasticity (CH), with approximately 60% of the materials tested lying in the first category and 40% in the second. The organic contents of most of these materials were between 4% and 8%, thus suggesting that they are basically intermediate organic soils.

SECTION 7

CONSOLIDATION AND COMPRESSIBILITY

The consolidation characteristics and compressibility of dredgings are two important properties that must be determined in order to assess the quality and potential usefulness of landfills composed of these materials. In general, maintenance dredgings have a high water content and contain substantial amounts of clay-like and/or organic materials, as well as various concentrations of pollutants; hence, their compressibility is usually large and the process of consolidation is quite time-consuming. Accordingly, this part of the overall study is directed toward evaluating the consolidation and compressibility characteristics of various dredgings from the vicinity of Toledo, Ohio. Fourteen slurry consolidation tests were conducted on slurry samples obtained during various stages of the dredging and deposition process, and an extensive series of 64 conventional consolidation tests was performed on "undisturbed" samples taken by piston sampler from different landfills. In addition, the secondary compression characteristics of eight undisturbed samples and two slurry samples were investigated, and time-dependent field settlements at several elevations are given for five locations in the Penn 7 Site.

TEST PROCEDURES

Fourteen slurry samples with an initial water content of about 150% to 200% were tested in specially designed slurry consolidometers (Sheeran and Krizek, 1971; Salem and Krizek, 1973). The loading scheme for these tests was similar to that normally used for a conventional consolidation test; a load increment ratio of unity was employed, and the load increments were 14, 28, 55, 110, and 220 kN/m^2. The first four load increments were applied for a period between 10 and 45 days to insure that primary consolidation was complete, and when primary consolidation due to the final load was essentially complete, the load was removed and the block of consolidated dredgings was extracted from the bottom of the test chamber. In two cases the final load increment was allowed to remain on the sample for 150 days to investigate the secondary compression, and in two other cases conventional consolidation tests were conducted on samples trimmed from the consolidated blocks.

Sixty-four undisturbed tube samples of dredged materials from three different landfills were tested by means of conventional consolidation tests. Sixteen of these samples were obtained from Riverside Site during the summer of 1972, and the other 48 samples were taken during the summers of 1973 and 1974 from Riverside Site, the Island Site, and Penn 8 Site. A 3-inch diameter, lightweight, manually operated piston sampler (Hummel and Krizek, 1974) was used to obtain all samples. For the first 16 specimens the initial load was 31 kN/m^2 and the maximum load was 248 kN/m^2; eight specimens were rebounded incrementally to the initial load, at which point the test was terminated, while the load of 248 kN/m^2 was maintained constant for over seven months on six samples and for ten months on two samples to investigate their secondary compression characteristics. The maximum load for the rest of the specimens reached 496 kN/m^2, after which all specimens were rebounded incrementally to 31 kN/m^2.

LABORATORY RESULTS AND ANALYSES

Presented in the following sections is a series of empirical relationships which may be used to estimate the magnitude and rate of settlement that might be anticipated in landfills composed of hydraulically placed maintenance dredgings. Relationships for the compression index and the coefficient of secondary compression are established as functions of the liquid limit, natural water content, dry unit weight, percent clay, and consolidation pressure, and the coefficient of consolidation is correlated with the consolidation pressure.

Compression Index

A study of the void ratio versus consolidation pressure curves for dredging slurries revealed a nearly linear plot in most cases for the last few load increments (Salem and Krizek, 1973). The compression index, C_c, was computed for each sample by taking the slope of a "best fit" straight line through the last two or three points; values for C_c would probably be lower if additional load increments (beyond 220 kN/m^2) were applied. The C_c values for virtually all of the dredging slurries tested were found to lie within a fairly narrow range of about 0.94 ± 0.17; C_c as a function of the liquid limit, w_L, may be described by the empirical equation

$$C_c = 0.02\, w_L - 0.44 \quad , \qquad (7\text{-}1)$$

where w_L is expressed as a percentage. Most observed values for C_c lie within 10% of the value predicted by Equation (7-1), but the range of liquid limit values is relatively small (60% to 76%).

The compression indices for the 64 samples tested in conventional consolidation tests varied between about 0.3 and 0.7, which lie in the lower portion of the 0.4 to 1.4 range reported by the Corps of Engineers (1969). When C_c is plotted versus the natural water content, w_n, and the liquid limit, w_L, respectively, the observed trend in both cases justifies the use of a first-order linear model, and the associated equations are

$$C_c = 0.01\,(w_n - 7) \pm 0.04 \qquad (7\text{-}2)$$

and

$$C_c = 0.008\,(w_L - 5) \pm 0.06 \quad , \qquad (7\text{-}3)$$

where w_n and w_L are expressed as percentages; these equations are similar to those reported by Terzaghi and Peck (1948), Van Zelst (1948), and Cozzolino (1961). For the work reported herein, the respective ranges of validity of Equations (7-2) and (7-3) are approximately $40 \le w_n \le 80$ and $45 \le w_L \le 90$, and the corresponding dimensionless correlation coefficients are 0.89 and 0.80. The simultaneous effect of both w_n and w_L on C_c may be expressed as

$$C_c = 0.04\ (w_L + 2\ w_n - 50) \quad , \qquad (7\text{-}4)$$

for which the computed multiple correlation coefficient is 0.88.

In two cases conventional consolidation tests were conducted on specimens trimmed from slurry consolidated blocks; these specimens were consolidated to a maximum consolidation stress of 1984 kN/m^2, and the resulting compression indices were 0.51 and 0.55, as compared with values of 0.80 and 0.90 obtained from the associated slurry consolidation tests, which attained a maximum consolidation stress of only 220 kN/m^2. The observed reductions in the values of C_c may be attributed to the fact that the virgin compression curves were not adequately defined in the slurry consolidation tests.

Coefficient of Consolidation

The coefficient of consolidation, c_v, corresponding to each load increment for slurry and conventionally consolidated samples was calculated from the relation

$$c_v = Th^2/t \quad , \qquad (7\text{-}5)$$

where t is time, h is the length of the shortest drainage path at the application of each load increment, and T is the time factor, which is a function of the degree of consolidation, U (taken to be 50% for the analyses conducted herein); in this study h equals one half of the specimen thickness because drainage took place in both tests from both the top and bottom. For the slurry samples the c_v values corresponding to consolidation pressures up to 220 kN/m^2 vary between a high of 0.00021 ± 0.00004 cm^2/sec and a low of 0.000025 ± 0.000011 cm^2/sec with an average value of 0.00011 ± 0.00002 cm^2/sec. The variation of the average coefficient of consolidation, $\bar{c}_v$, with consolidation pressure, p, is given in Figure 7-1 together with the average values and ranges of the 70 percentile (70% of the values lying within this range) and may be described within very broad limits by the empirical equation

$$\bar{c}_v = (18 - 3.3 \log p)\ 10^{-5} \quad , \qquad (7\text{-}6)$$

where p must be expressed in kN/m^2 and $\bar{c}_v$ is determined in units of cm^2/sec. The observed variations in c_v for a given dredging sample are consistent with previous experience on a variety of clayey soils. For all practical purposes the coefficient of consolidation obtained from slurry consolidation tests can be taken as 10^{-4} cm^2/sec.

For conventionally consolidated tube samples the ranges and means of the c_v values corresponding to the various consolidation pressures are shown in Figure 7-1. Although this relationship exhibits a minimum for c_v at a consolidation pressure of about 125 kN/m^2, a reasonably constant value of about 0.0006 cm^2/sec can be used to characterize the time dependency of the consolidation response of these dredgings (except for the somewhat higher c_v values at the lowest consolidation pressure, 31 kN/m^2). The manifested variation of $\bar{c}_v$ with p is similar to those reported by Taylor (1948) for

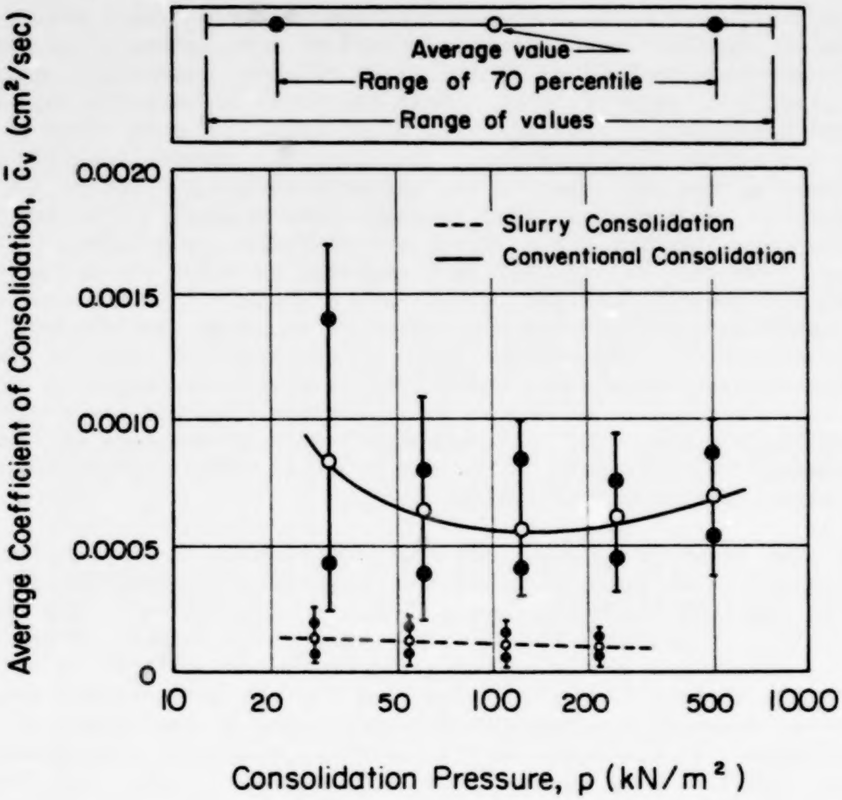

Figure 7-1. Average Coefficient of Consolidation versus Consolidation Pressure

Boston blue clay, Chicago clay, Newfoundland silt, and Newfoundland peat. The average value of c_v obtained from conventional consolidation tests is about six times that obtained from slurry consolidation tests; this may be attributed in part to the variation in the thickness of the samples whereby higher gradients were developed in the samples with the smaller thickness. (The thicknesses of the samples at the end of the slurry and conventional tests were about 15 cm and 2 cm, respectively.) This same explanation can be offered as the reason for the increase in c_v with consolidation pressure for values of the latter greater than 125 kN/m^2 in the case of conventional tests. However, it is probable that much of the observed difference in behavior was caused by the different ways in which the samples were prepared and consolidated.

Secondary Compression

The long-term compression-time curves (Krizek and Salem, 1974) of the slurry consolidated samples and the undisturbed tube samples both manifested a double-S pattern. Upon completion of primary consolidation, the secondary compression of all samples increased in essentially a linear manner with the logarithm of time for a considerable period of time, after which the rate of secondary compression became significantly greater, reaching a maximum and then decreasing to zero at large times; this type of behavior suggests that a structural breakdown of interparticle bonds occurs at some value of strain for each particular load increment. Although the unusual behavior pattern which starts at the beginning of the second S-shaped portion of the response curves for the conventional consolidation tests resembles that obtained from the slurry consolidation tests, there are different proportions of secondary to primary compressions and the times required to reach the end of primary consolidation and ultimate settlements are different. In the case of the slurry consolidation tests the proportion of secondary compression to total compression is about 0.25 whereas it is on the order of 0.60 for the conventional consolidation tests for essentially the same increment of applied stress; both ratios were evaluated at long times when the rates of settlement were essentially zero. This phenomenon may be a consequence of the different thicknesses of the specimens in the two types of test; such behavior is consistent with the findings of Barden (1965).

The time required to reach ultimate settlements is shorter for the slurry consolidation tests than for the conventional consolidation tests even though the specimen thickness in the former is about five or six times that in the latter. Alternatively, the time required to complete primary consolidation (as determined by the conventional Casagrande method) in the slurry consolidation tests is about 30 times that for the conventional consolidation tests; these times are approximately proportional to the square of the specimen thicknesses, as predicted by the classical theory of consolidation (Terzaghi, 1923). These observations suggest that (a) the time required to reach ultimate settlements (including secondary compression) does not necessarily have to be longer for greater thicknesses of material and (b) the relative amount of secondary compression that occurs in the field, where the thickness of material is normally much larger than that in the laboratory, may be considerably less than the value predicted from laboratory tests. The average ultimate settlement for the specimens in the slurry consolidation tests was about 10% under the final load increment (110 to 220 kN/m^2) whereas it was about 14% for the specimens in the conventional tests for essentially the same load increment (124 to 248 kN/m^2). A comparison of final settlements and the corresponding stresses indicates that the rates of settlement are approximately the same despite the variation in the time needed to attain such settlements and the proportions of secondary to total settlements.

Average underestimations in the values of secondary compressions due to a linear extrapolation of the straight line portions of the compression-log time plots were about 45% and 60% for slurry and conventional consolidation tests, respectively, whereas average underestimations in secondary compression with respect to total compressions were about 10% and 35% for the two types of tests. These results suggest that data from the slurry consolidation tests on the thicker specimens may be sufficient to predict ultimate settlements, once the slope of the straight line portion of the consolidation curve is defined and the ratio between the secondary and total settlement is known, but the use of similar data from conventional consolidation tests should be made with considerably more caution.

Coefficient of Secondary Compression

The coefficient of secondary compression, C_a, can be expressed as

$$C_a = (\Delta h/h)/(\Delta \log t) \quad , \qquad (7\text{-}7)$$

where Δh is the reduction in specimen thickness for a given change in time (represented by $\Delta \log t$) and h is the thickness of the specimen at the time the load increment under consideration is applied. Despite variations in the proportions of secondary to primary settlements and underestimations of settlements due to a linear extrapolation of the settlement-log time curves after primary consolidation, the values of the coefficient of secondary compression, C_a, from both slurry consolidation and conventional consolidation tests are practically the same, varying from 0.0072 to 0.0085 and from 0.0073 to 0.0128, respectively, for the last load increment. Accordingly, a knowledge of the relationships between this coefficient and certain other properties of dredgings, together with information concerning the relative proportions of secondary and total settlements and the settlement-time behavior of the primary portion of consolidation, will enable the engineer to estimate the extent of the expected settlements due to secondary compression. C_a was found to increase in a reasonably linear manner with the logarithm of p for the eight dredging samples tested by use of conventional consolidation tests; in general, a different relationship was obtained for each specimen, but all straight lines were approximately parallel with a change of about 0.006 in the value of C_a for a change in pressure from 31 kN/m^2 to 248 kN/m^2. A reasonably good straight line relationship was obtained between the logarithm of C_a and the logarithm of w_n for a given load increment; values of C_a ranged from about 0.002 to 0.013 for a natural water content range from 45% to 65%. Values of the compression index, C_c, determined from the e-log p curves, varied between 0.32 and 0.55, and, as shown in Figure 7-2, C_a showed a generally linear increase with an increase in C_c for a given load increment.

FIELD SETTLEMENTS

The field measurement of settlements and pore water pressures is usually accomplished by means of settlement plates and piezometers, and the accessibility of this instrumentation is as important as its performance. For landfills composed of dredged materials the conditions that exist during the process of deposition pose a particularly difficult access and installation problem because most of the units must be placed while the fill material is in a slurry form.

Original plans included the placement of settlement plate-piezometer units at four different elevations (original ground and about 1-meter intervals during the deposition of dredged materials) at each of ten locations in the Penn 7 Site, as shown in Figure 4-3. Due to various factors (weather conditions, vandalism, inaccessibility, etc.), five of these units were lost or destroyed before installing others at higher levels, and they could not be replaced; subsequently, it was decided to omit all units at these locations because the settlement at the bottom boundary could not be monitored. All other units were placed at the remaining locations (2/10, 5/8, 5/10, 5/13, and 15/10) at appropriate times during the dredging and disposal process, but a few of these units were lost or destroyed subsequently due to vandalism.

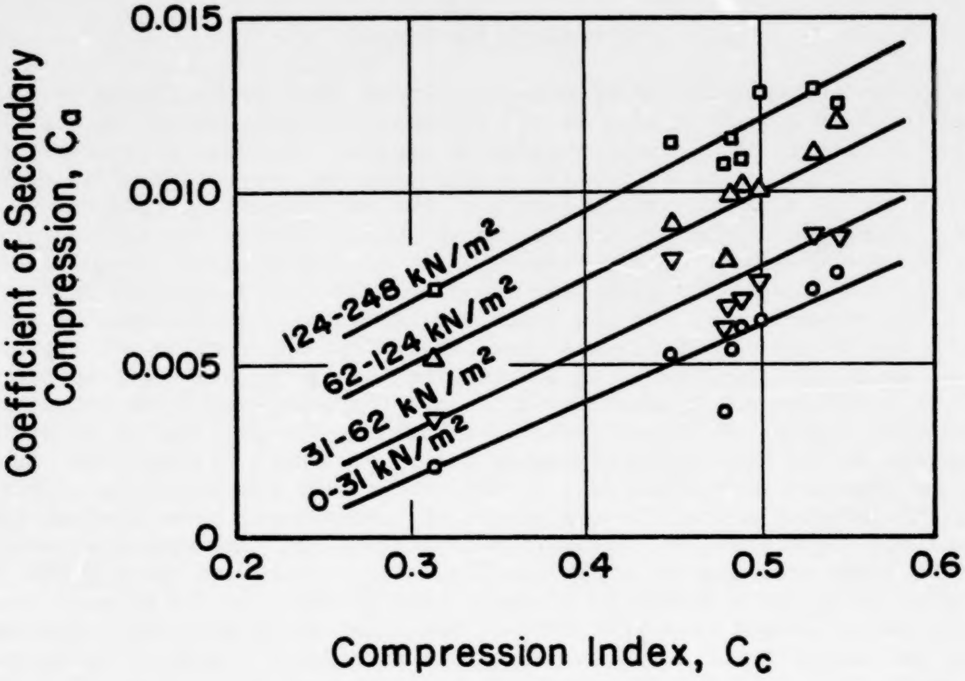

Figure 7-2. Coefficient of Secondary Compression versus Compression Index

Figure 7-3 shows the measured settlements and piezometric heads for two units at location 2/10 and three units at each of locations 5/8, 5/10, 5/13, and 15/10. (No water heads were measured at location 2/10.) The latest installed units near the surface of the fill were dry throughout the period of observation; hence, records of piezometric heads are given only for the deeper units. The monitoring of settlements started about 280 days after placing the set of bottom settlement plates and continued thereafter for about 440 days. Some of the units were destroyed at intermediate times, and therefore complete sets of data are not available for all locations. Observed settlements varied between about 0.2 to 0.5 meter for bottom units and about 0.2 to 0.8 meter for plates near the surface of the fill. Piezometric heads above the midheight of the porous tips indicated values near the elevation of the fill surface for a long time, but a considerable drop was measured in August of 1974.

In addition to the settlements measured at the Penn 7 Site, surface settlements were monitored at various locations at Riverside Site for several years. The measured settlements at both sites are compared (Krizek and Salem, 1974) with those computed from a simple model based on the classical

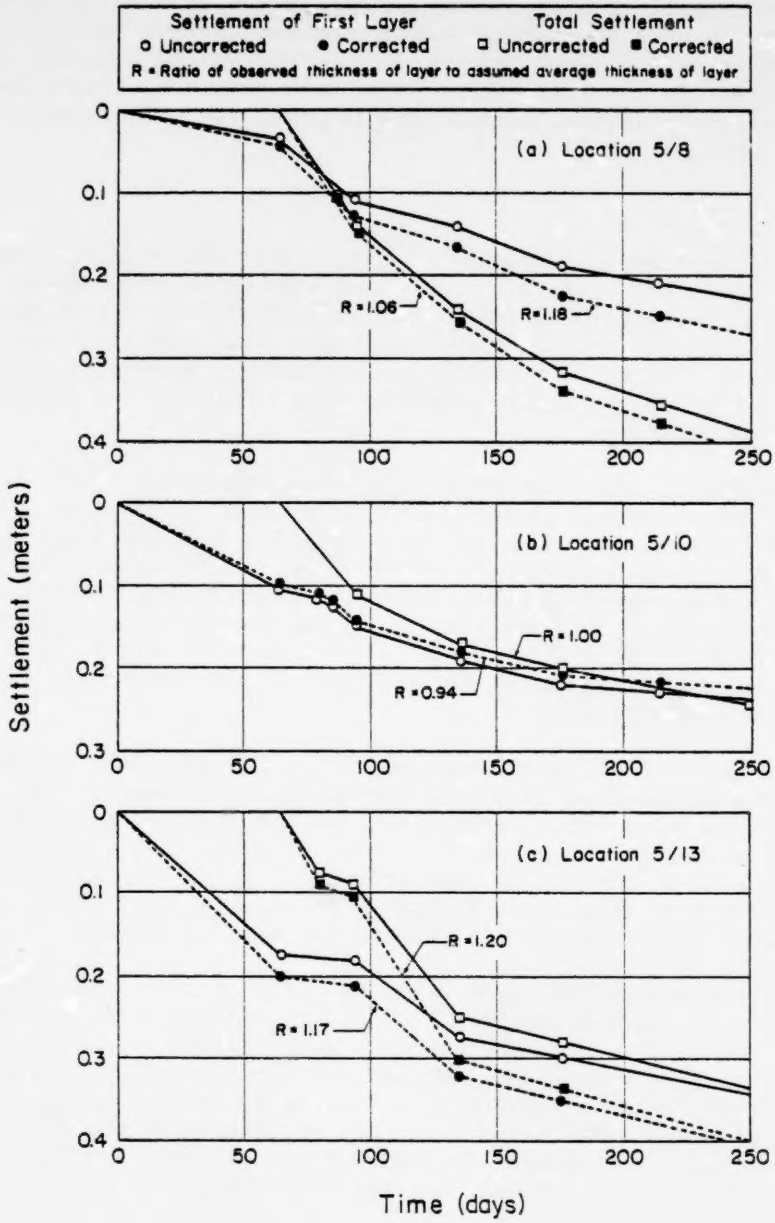

Figure 7-3. Measured Field Settlements and Piezometric Heads

theory of consolidation, and a more sophisticated model (Krizek and Casteleiro, 1974) that accounts for both consolidation and desiccation, as well as a nonhomogeneous distribution of mechanical properties in the vertical direction, is used to compute comparative settlements for the Penn 7 data only. In each case the input information was determined, insofar as possible, by laboratory and field tests; when appropriate test data were unavailable or inconclusive, engineering judgment was used to select the input parameters.

CONCLUSIONS

Although the samples investigated herein were all obtained from the Toledo area, these materials are typical of many maintenance dredgings, and it is felt that the empirical relationships established in this study will be reasonably applicable for all dredged materials that possess similar classificatory indices. Based on the analysis and interpretation of the data obtained from the field and laboratory testing programs, the following conclusions can be advanced:

1. The compression index obtained from conventional tests lies between 0.3 and 0.7 and increases linearly with both water content and liquid limit; its value obtained from slurry consolidation tests is about 1. For all practical purposes values of 0.0006 cm^2/sec and 0.0001 cm^2/sec can be assumed to represent the average coefficient of consolidation obtained from conventional consolidation tests and slurry consolidation tests, respectively. The difference in the values of C_c and c_v from both tests is attributed primarily to the variation in the nature of deposition of the tested materials.

2. After primary consolidation was complete, the secondary compression of all samples tended to increase in essentially a linear manner with the logarithm of time for a considerable period of time, after which the rate of secondary compression increased significantly, reaching a maximum and then decreasing to zero at large times. This type of behavior suggests that a structural breakdown of interparticle bonds occurs at some value of strain for each particular load increment.

3. Despite the significant difference in the proportions of secondary and primary compressions obtained from slurry and conventional consolidation tests, the total settlement per unit height associated with corresponding stress levels is about the same for both tests; the times necessary to reach ultimate settlements are shorter for slurry consolidation tests than for conventional tests, and this suggests that the times needed to reach ultimate settlements in the field may be much shorter than those predicted from conventional consolidation tests.

4. The coefficients of secondary compression from both slurry and conventional consolidation tests are practically the same for corresponding ranges of load, irrespective of the method of testing and the ratios of secondary to total settlements from each test, and values ranged between 0.002 and 0.013 for a natural water content range from 45% to 65%, increasing as a power function for a given load increment.

In addition, the coefficient of secondary compression increased exponentially with the consolidation stress for a given natural water content and linearly with the compression index for a given load increment.

SECTION 8

PERMEABILITY AND DRAINAGE

The potential usefulness of fine-grained maintenance dredgings for landfill depends to a large extent on the ease with which these sediments can be dewatered from a slurry to a solid state. Accordingly, several series of field and laboratory tests were conducted to examine the permeability and drainage characteristics of a number of typical dredgings from various harbors around the Great Lakes, but the majority of the tests were performed on materials from the vicinity of Toledo, Ohio. Slurry samples were taken either from the fill area or directly from the inlet pipes through which the materials were pumped, and undisturbed samples of existing landfills were obtained by means of a manually operated, specially designed, piston sampler (Hummel and Krizek, 1974).

TEST PROGRAM

Three series of drainage tests were conducted to study the rate of water loss from several different dredged materials due to (a) gravity only, (b) gravity plus vacuum with the air pressure being applied directly to the surface of the dredgings, and (c) gravity plus vacuum with a membrane between the surface of the dredgings and the atmosphere. The test equipment consisted of a series of Plexiglas cylinders (7½ or 15 cm in diameter and 50 or 60 cm high) with porous stones fitted into the bottom of each cylinder; the effluent was collected in bottles, and the bottle was either vented to the atmosphere for gravity drainage or connected to a vacuum line for vacuum drainage. Two variations of vacuum drainage were used; in the first the air pressure due to the atmosphere was applied directly to the surface of the dredgings whereas in the second a membrane was placed between the dredgings and the atmosphere. Although all tests were conducted in a humid room to minimize incidental water losses, it was found during the first test series that significant moisture was still being lost through the top surfaces; hence, one improvement in the second and third series was to use a smooth fitting Plexiglas disk for the top plate (Krizek, Karadi, and Hummel, 1973). The average flow rate was determined from the total amount of water drained in a given period of time; then, with a knowledge of the sample height and the height of the water, the gradient was calculated and the permeability was computed by use of Darcy's law. In the case of the vacuum tests, the vacuum was converted to an equivalent head.

The Anteus consolidation device (Lowe, Jonas, and Obrician, 1969) was used to conduct several direct permeability tests. Undisturbed samples were trimmed to fit the consolidometer ring, placed in the device, and subjected to 80 psi (550 kN/m^2) backpressure to achieve a high degree of saturation.

After being consolidated under a 10 psi (70 kN/m^2) stress for at least 12 hours, the samples were unloaded and tested to determine their permeability while still under the backpressure. The permeability values were calculated by use of the standard expression for a falling head permeability test. The coefficient of permeability was also backcalculated from conventional consolidation test data (Krizek and Salem, 1974) on undisturbed specimens and from slurry consolidation test data on slurry samples. A series of electro-osmosis tests with average electrical gradients of 0, ½, and 1 volt per centimeter and a pressure gradient of approximately 0.5 lb/in^2/in (1.4 kN/m^2/cm) was conducted on four dredging samples (Krizek, Karadi, and Hummel, 1973). In an effort to shed some light on the in situ field permeability of a landfill composed of dredged materials, two infiltration tests were conducted at Riverside Site in Toledo, Ohio; the majority of the dredgings in this disposal area were placed in the late 1960's and 1970, and the deposit is about 4 meters (13 feet) deep. The water table is about 0.4 to 0.8 meter (1.3 to 2.6 feet) below the surface, and wells with a perforated tip surrounded by a sand filter were placed approximately 2 meters (6.5 feet) deep. The wells were pumped dry and the time rate of recovery was measured; data were interpreted according to the procedure outlined by Lambe and Whitman (1969; pp. 284-285, Case G) with the assumption that the coefficient of permeability is isotropic.

RESULTS

Data from seven different types of permeability tests are summarized in Figure 8-1; the different testing techniques include conventional consolidation, single-load consolidation, slurry consolidation, direct permeability, gravity drainage, vacuum drainage, and field infiltration. In general, these test data fall into three groups; the results from the gravity drainage tests span a permeability range between 10^{-4} and 10^{-6} cm/sec (100 and 1 ft/yr) and a corresponding void ratio range between 2 and 10; ranges of permeability and void ratio of 10^{-6} to 10^{-7} cm/sec (1 to 0.1 ft/yr) and 1 to 5, respectively, are associated with vacuum drainage; the consolidation and direct permeability test data lie within a permeability range between 10^{-6} and 10^{-9} cm/sec (1 and 0.001 ft/yr) and a void ratio range between 1.0 and 1.5; although the void ratio range for the field infiltration tests is between 1.0 and 1.5, the permeability values are generally between 10^{-4} and 10^{-5} cm/sec (100 to 10 ft/yr), or about three orders of magnitude higher than those measured in the laboratory tests. Despite the relatively wide scatter in the data plotted in Figure 8-1, a distinguishable trend is evident in the relationships between permeability and void ratio; the solid and dashed curves represent suggested average values and ranges, respectively, for the coefficient of permeability as a function of void ratio.

Drainage

Based on data from five typical dredged materials tested under three different drainage conditions, it was found that (a) the use of a vacuum extracted significantly larger quantities of water from the dredgings than did gravity alone and (b) the major effect of the vacuum occurs during the initial time period. For example, the drainage quantities after one day with vacuum were from one and a half to five times the quantities obtained for gravity alone; viewed differently, the quantity of drainage with vacuum during the first five hours was about the same as by gravity alone for the first day or two while the drainage by vacuum for one day was comparable to that by gravity alone for about a week. After three weeks, the quantities of drainage by gravity alone were about one half of those achieved by vacuum for all samples. Although extracting greater quantities of water in a given time, the vacuum tests employed a greater applied head and thus generated a greater flow resistance; the head for the vacuum test was about twenty times that for the gravity test, and the flow resistance was increased by a factor of about ten, as reflected in the lower values of permeability for the vacuum tests.

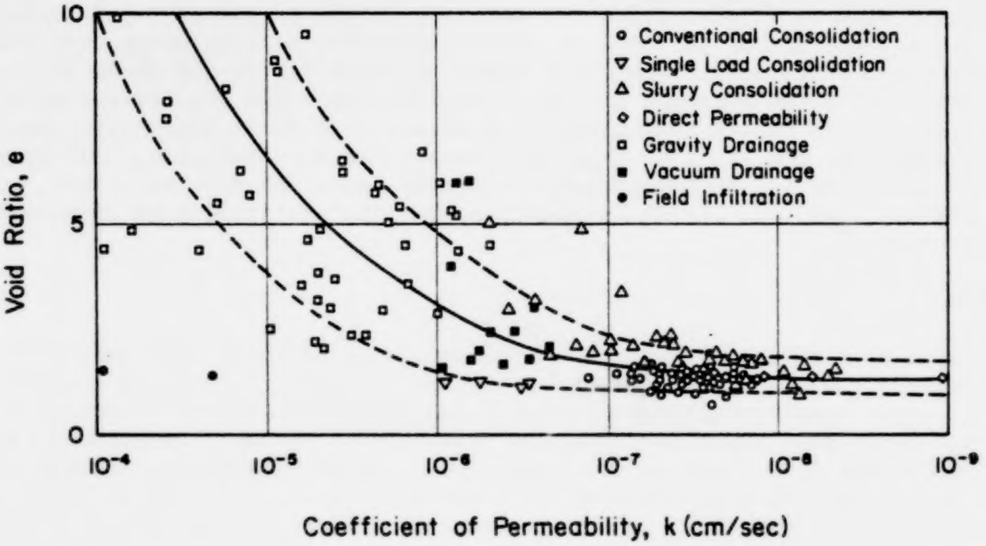

Figure 8-1. Summary of Values for Coefficient of Permeability

Depending on the water content of the material and the applied hydraulic gradient, the drainage times for these samples ranged from about one day to in excess of a hundred days. Since these tests extended over long periods of time, it was possible to approximate the permeability at points throughout the drainage process; an incremental flow quantity was averaged over a short period of time, and this value, together with the head and length of flow path associated with that time, were used to compute the coefficient of permeability.

Direct Permeability

Six direct permeability tests yielded coefficients of permeability ranging from about 5 x 10^{-8} to 10^{-9} cm/sec (0.05 to 0.001 ft/yr) with the bulk of the values centering around 10^{-8} cm/sec (0.01 ft/yr). These values coincide approximately with the lower permeability values obtained from the slurry consolidation tests.

Conventional Consolidation

Two series of conventional consolidation tests were conducted on undisturbed tube samples of typical dredged materials from two disposal sites near Toledo, Ohio. In the first series, the data from which are plotted in Figure 8-1, the range of consolidation stress was relatively low (up to 36 psi or 248 kN/m^2) and permeability values lay between 2×10^{-8} and 4×10^{-8} cm/sec (0.02 and 0.04 ft/yr) with no apparent correlation with the effective particle size ($0.0004 \text{ mm} < D_{10} < 0.0005 \text{ mm}$), percent clay ($30 < \% \text{ clay} < 50$), coefficient of uniformity ($15 < C_u < 40$), or liquid limit ($45 < w_L < 85$). These values are comparable to those obtained from the slurry consolidation tests for the same range of consolidation stresses. In the second series, the results of which are given in Figure 8-2, permeability values were determined over a much wider range of consolidation stress (namely, double the range investigated in the first series). A typical plot of the permeability versus the void ratio for a given sample subjected to a given load increment is shown in Figure 8-2a, and similar plots for all samples subjected to five different load increments are given in Figures 8-2b to 8-2f. All data plotted in Figures 8-2b through 8-2f are replotted on the general correlation graph in Figure 8-2g, and the resulting empirical relationship can be described by

$$k = \log_{10}^{-1} (1.35 e - 9) \quad , \tag{8-1}$$

where k is expressed in cm/sec. Most of these permeability values lie between 10^{-6} and 10^{-8} cm/sec (1 and 0.01 ft/yr) and coincide with those found from the direct permeability tests.

Slurry Consolidation

The coefficient of permeability was evaluated from 12 slurry consolidation tests at stresses up to 224 kN/m^2 (32 psi), and average values can be reasonably well described by the empirical expression

$$k = \log_{10}^{-1} (1.35 e - 10) \quad , \tag{8-2}$$

where k is expressed in cm/sec. A comparison of Equations (8-1) and (8-2) indicates a similar rate of change of permeability with respect to void ratio, but there is a difference of one order of magnitude between the two empirical expressions. Since both equations cover approximately the same lower range of void ratio ($0.8 < e < 2.0$ for the conventional consolidation tests whereas $0.9 < e < 5.0$ for the slurry consolidation tests), the lower permeability values backcalculated from slurry consolidation tests must be attributed to the testing technique; apparently the particle arrangements of slurry consolidated dredgings in the laboratory are different than those of hydraulically placed dredged materials that consolidate in the field under their own weight. Data from a limited number of conventional consolidation tests on samples trimmed from slurry consolidated blocks suggest that the rate of change of permeability with respect to void ratio will increase as the consolidation stress increases (to 256 psi or 1800 kN/m^2) and the void ratio decreases (to e of 0.5).

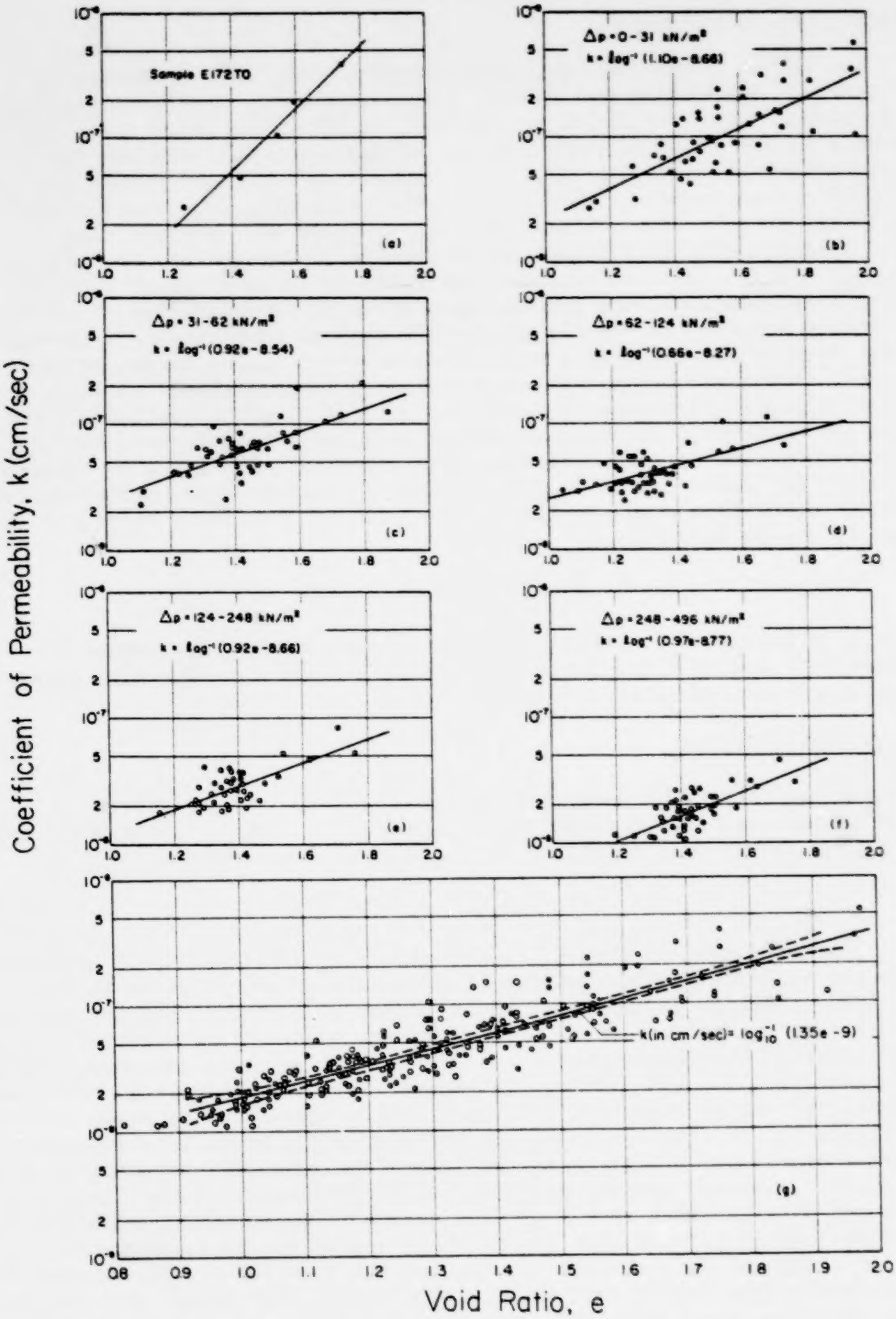

Figure 8-2. Coefficient of Permeability versus Void Ratio for Conventional Consolidation Tests

Electro-Osmosis

The electro-osmotic coefficient of permeability ranged from about 1.5×10^{-5} to 4.5×10^{-5} cm^2/volt-sec. These values are approximately one half of the values associated with a large variety of soils. However, the problems associated with extrapolating these limited laboratory data on small samples to field cases involving substantially larger dimensions must be approached with caution.

Field Tests

The results from two field infiltration tests reveal permeability values of approximately 10^{-4} cm/sec (100 ft/yr) for the well located in about the middle of the disposal area and approximately 10^{-5} cm/sec (10 ft/yr) for the well near the outflow weir. These values are both consistent with engineering reasoning. First, both values are significantly higher (three orders of magnitude) than those obtained from laboratory tests on samples from essentially the same locations; the observed discrepancies are likely due in large part to the seasonal stratifications associated with dormant periods between dredging seasons. And second, the permeability value determined from the well near the outflow weir is about one order of magnitude smaller than that obtained from the well in the middle of the disposal area; this may be readily explained by the fact that the finer materials tend to accumulate near the overflow weir.

SUMMARY

The drainage characteristics of a given material were found to depend on the nature of the solids and the fluids, as well as the water content at the time of drainage. Different dredgings drain at different rates and are affected to different degrees by the application of a partial vacuum. In general, vacuum drainage was found to remove water from dredgings much faster than gravity drainage alone, and it allowed greater amounts of water to be extracted in a given period of time. However, the maximum effect of vacuum on the drainage response was achieved during the initial time period, and less significant effects were observed over longer periods of time.

The coefficient of permeability is strongly dependent on the void ratio and decreases from about 10^{-4} to 10^{-9} cm/sec (100 to 0.001 ft/yr) as the void ratio decreases from approximately 10 to 1. Most permeability values for the firmer materials, which had void ratios on the order of 1 to 2, were in the range of 10^{-7} to 10^{-8} cm/sec (0.1 to 0.01 ft/yr). Field infiltration tests yielded permeability coefficients approximately three orders of magnitude higher than those obtained from laboratory tests on undisturbed and remolded samples with comparable void ratios. The electro-osmotic coefficient of permeability was found to be about 3×10^{-5} cm^2/volt-sec, which is approximately one half the value determined for a large variety of soils.

SECTION 9

SHEAR STRENGTH

An extensive field and laboratory test program was conducted to obtain information on the shear strength characteristics of dredged materials. Field tests were performed at the four Toledo disposal sites (Island, Riverside, Penn 7, and Penn 8) at the locations indicated in Figure 4-3.

TEST PROGRAM

Thirty-one strength profiles were obtained during the years from 1971 to 1974, and 90 undisturbed piston samples were taken at the same times and locations that field vane tests were performed in order to compare field vane strength values with those determined in the laboratory by means of miniature vane tests, cone penetration tests, and unconfined compression tests. In addition, correlations were established between shear strength and various other index properties.

The Swedish vane borer (Cadling and Odenstad, 1950) with a vane 6.5 cm in diameter and 13 cm in height and a vane rotation of six degrees per minute was used for the in situ shear strength determinations reported herein. After the peak torque was reached and recorded, the vane shaft was rotated rapidly through 20 revolutions to remold the soil in the zone where the shear strength was determined, and the test was repeated in the usual manner to measure the remolded strength. The miniature vane apparatus used for these tests was designed and manufactured in England by Leonard Farnell and Company, Limited; the diameter and height of the vane were both 0.5 inch (1.25 cm), and the rotation rate was six degrees per minute. Although the cone penetration test employed in this study is widely used in the laboratory to evaluate the consistency or shear strength of soft cohesive soils (Skempton and Bishop, 1950), the empirically determined cone factor was found in previous studies to be strongly dependent on the type of clay and to vary with water content for a given clay; accordingly, the cone test can be considered only as a rough approximation to the undrained shear strength of a clay. Even as a measure of the sensitivity of one particular clay, the cone test can be misleading because the cone factor (which depends on the ratio of the soil modulus to the shear strength) will generally be different for undisturbed and remolded soils. Standard unconfined compression tests were conducted on specimens with a length-to-diameter ratio of about 2 to 2.5; the height of these specimens varied between 7.5 cm and 10 cm and the diameter varied between 3.5 cm and 4 cm. A constant strain rate of approximately 1% per minute was used for all tests.

RESULTS

Three typical plots of shear strength versus depth, together with the associated values of water content, Atterberg Limits, percent clay, and dry density, are shown in Figure 9-1. Although the shear strength values are quite low, they are generally comparable to those of ordinary fine-grained soils with similar water contents and dry densities. Similar trends were found at all four sites except at locations close to the inlet pipe where the material becomes more granular.

Physical reasoning suggests that the shear strength of a layer of dredged material should be highest at the top (where desiccation and evapotranspiration have lowered the water content considerably) and bottom (where some consolidation has taken place due to the overburden of dredged material and drainage into the underlying foundation soil) and lowest in the middle (where less consolidation and no desiccation have occurred); such profiles are illustrated typically in Figure 9-1. Although this anticipated profile was found at many locations, there were some variations due to the existence of preconsolidated layers at intermediate depths (caused by desiccation between dredging seasons).

In general, the shear strength at a given site in a given year was found to increase with horizontal distance from the overflow weir. For example, Figure 9-1 shows that the 1973 field vane strengths at a depth of 0.6 meter at locations 1, 6, and 8 of Riverside Site are 7, 17, and 24 kN/m^2, respectively, and laboratory vane strengths at the same locations at a depth of slightly more than 1 meter are 15, 27, and 60 kN/m^2. This variation is probably due in large part to the grain size distribution in a typical site since the coarse particles tend to settle near the inlet pipe and the fine particles settle closer to the overflow weir; in addition to strength variations that are related directly to variations in particle sizes, the coarse material drains and consolidates faster, thereby developing greater strength in a given period of time. At all four sites field vane tests could not be conducted over more than about two thirds of the distance from the overflow weir to the inlet pipe because the fill material near the inlet pipe was too granular and dense to allow the vane to be advanced manually.

Since field vane tests were conducted at all four sites during the early summer of each year from 1971 to 1974 and since the sites each had a different time history beginning about a decade ago, the variation of strength with time could be studied. In general, the strengths measured in any given year are somewhat greater than those measured in a preceding year, but the evidence is not entirely consistent. The reasons for the manifested inconsistencies are varied, but they seem to frequently relate to the water content of the dredged material as affected by the immediate past history of the site. For example, one inconsistency was observed near the overflow weir at the Island Site where the 1971 strength values were higher than those of 1973; however, field records indicate that there had been an unusual rise in the water level of Lake Erie for several days during the month of April 1973, and this caused part of the Island Site close to the overflow weir to be flooded. The effect of this flooding was noticed a few months later when the field tests were conducted; the surface of the fill was very wet compared to

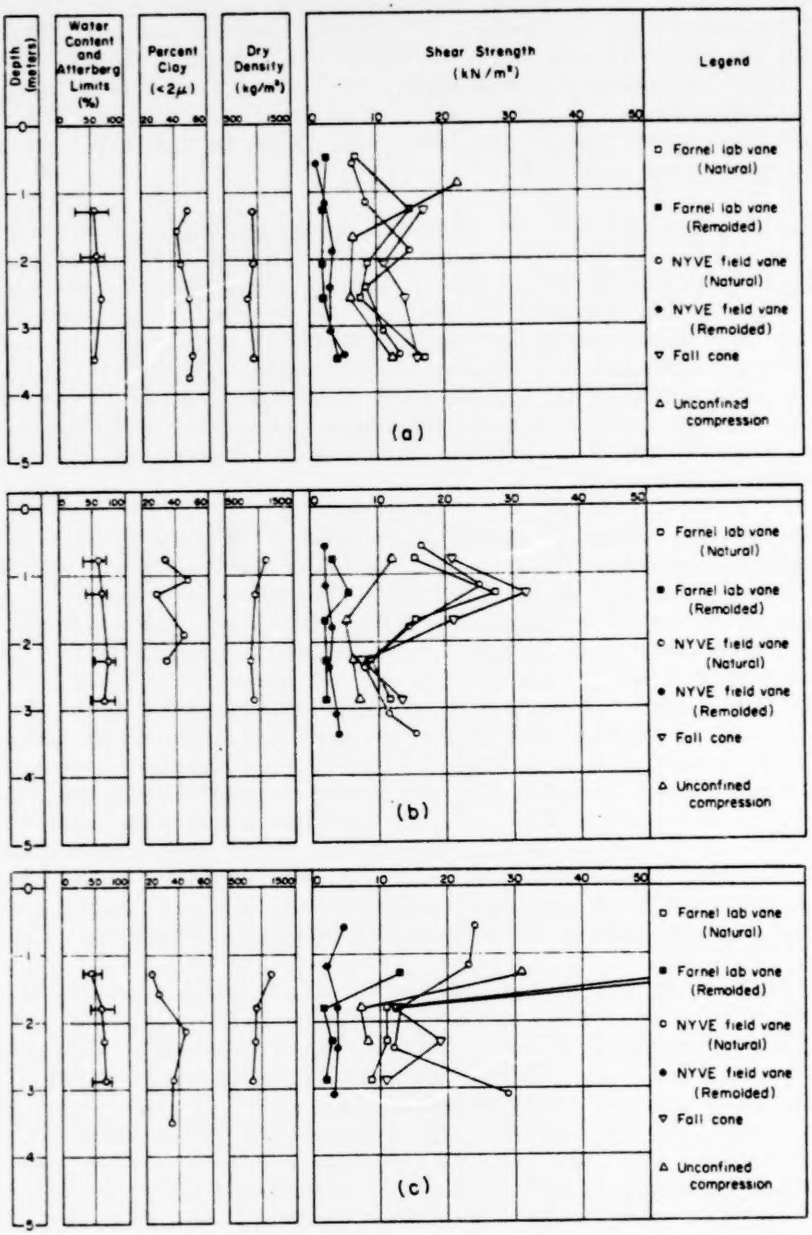

Figure 9-1. Typical Profiles at Riverside Site in 1973

that in 1971, and several pools of water were found. As a consequence, the water content of the dredged material increased from 1971 to 1973. Another condition which may have contributed to the higher water content and associated loss of strength is the fact that dredged spoil was pumped into the area for four months immediately after the 1971 field program was completed. (Field tests were conducted in June of 1971, and pumping was done from August to November of the same year.) The amount of dredgings placed during these four months was 16% of the total material deposited in the years before 1971.

Since an extensive series of characterization tests indicated that the dredged materials deposited in all four sites were generally similar, the time-dependent strength response at each of these sites can be combined and treated as one representative site which has a history covering the life spans of the four individual sites. The thickness of the fill in each site is nearly equal, and this tends to justify the elimination of this parameter (which reflects the drainage effectiveness) from the analysis. However, because the placement of dredgings into a given site took place discontinuously during several dredging seasons, the synthesis of the strength response from these four sites necessitates that an "equivalent zero time" or "birthdate" be established for each site. For this purpose the time corresponding to the placement of one half of the final volume of dredgings in a site is arbitrarily assumed to be the equivalent zero time for that site; accordingly, as illustrated in Figure 4-2, 1967, 1968, 1972, and 1966 were taken to be the birthdates of the Island Site, Riverside Site, Penn 7, and Penn 8, respectively. Within the framework of this assumption, the average shear strength, s_{avg}, defined as the integral of the shear strength profile over a given depth divided by the corresponding depth, was found to be given by

$$s_{avg} = [2.9 + 2(x/\ell)][t - 1.0] \quad , \qquad (9\text{-}1)$$

subject to the constraints that $x/\ell < 0.7$ and $1 \le t \le 10$, where x is the distance of the test location from the overflow weir, ℓ is the distance between the overflow weir and the inlet pipe, t is expressed in years, and s_{avg} is expressed in kN/m^2.

Many normally or lightly overconsolidated clays and silts manifest a reduction in strength upon remolding, and in some problems the fact that a soil may be sensitive is as important as its undisturbed strength. The undrained strength and sensitivity can be obtained from vane tests, and these two parameters have been found to give a very characteristic description of a clay (Andresen and Bjerrum, 1958). Values of sensitivity ranged from about 2 to 10 for the field vane tests and from about 3 to 7 for the laboratory vane tests although considerable scatter was observed. In general, for lower values of natural water content and liquidity index and higher values of dry density, the sensitivity measured by the field vane is higher than that measured by the laboratory vane, and it is relatively unaffected by the independent variable in the case of high values of natural water content and liquidity index and low values of dry density. The measured sensitivity values place many of these dredgings in the category of "sensitive" soils according to the classification given by Terzaghi and Peck (1968).

Correlation between Shear Strength and Index Properties

The measured field and laboratory strengths (designated as s_{fv} for the field vane, $s_{\ell v}$ for the laboratory vane, s_{fc} for the fall cone, and s_{uc} for the unconfined compression tests) are correlated in Figures 9-2, 9-3, and 9-4 with the natural water content, w_n, dry density, γ_d, and liquidity index, LI, respectively. Figure 9-2 shows the correlations between the various shear strengths and the natural water content. All of these relationships can be reasonably well described by an equation in the form

$$\log s = a_w e^{-b_w(w_n - 40)} \quad , \qquad (9\text{-}2)$$

where a_w and b_w are empirical constants that depend on the type of test. To select the "best" estimate for these two constants, Equation (9-2) was transformed to a linear equation, and the stepwise regression method tempered with engineering judgment was used to determine the a_w and b_w values listed in Table 9-1. The measured strengths are plotted in Figure 9-3 and 9-4 as functions of the dry density and the liquidity index, respectively, and the data in each case manifest a linear variation between the logarithm of strength and both variables; these relationships can be represented in general form by

$$\log s = a_\gamma[(\gamma_d/\gamma_w) - b_\gamma] \qquad (9\text{-}3)$$

for the dependence of s on γ_d, and by

$$\log s = a_L(b_L - \text{LI}) \qquad (9\text{-}4)$$

for the dependence of s on LI. Values of the constants a_γ, b_γ, a_L, and b_L are given in Table 9-1. In all cases the correlation coefficients are on the order of 0.7 to 0.9. In the case of the latter two variables, multiple regression analyses were performed, and the following equations with correlation coefficients of 0.87, 0.91, 0.92, and 0.84, respectively, were obtained:

$$\log s_{fv} = 0.07 + 1.8\ \gamma_d/\gamma_w - 0.55\ \text{LI} \qquad (9\text{-}5)$$

$$\log s_{\ell v} = 0.09 + 2.0\ \gamma_d/\gamma_w - 0.63\ \text{LI} \qquad (9\text{-}6)$$

$$\log s_{fc} = 0.22 + 2.0\ \gamma_d/\gamma_w - 0.80\ \text{LI} \qquad (9\text{-}7)$$

$$\log s_{uc} = 0.68 + 0.9\ \gamma_d/\gamma_w - 0.96\ \text{LI} \qquad (9\text{-}8)$$

An examination of the comparisons plotted in Figures 9-2, 9-3, and 9-4 indicates that the strength values determined by means of the four tests described are usually highest for the fall cone and decrease in the order of laboratory vane, field vane, and unconfined compression tests. In general, the strengths measured by the field vane and the laboratory vane are in reasonably good agreement, but strength values obtained from unconfined compression tests are almost always considerably lower than values obtained from any other test; very often there is a factor of two between the strengths determined by an unconfined compression test and a fall cone test. This can be attributed in large part to the strength loss associated with sampling and

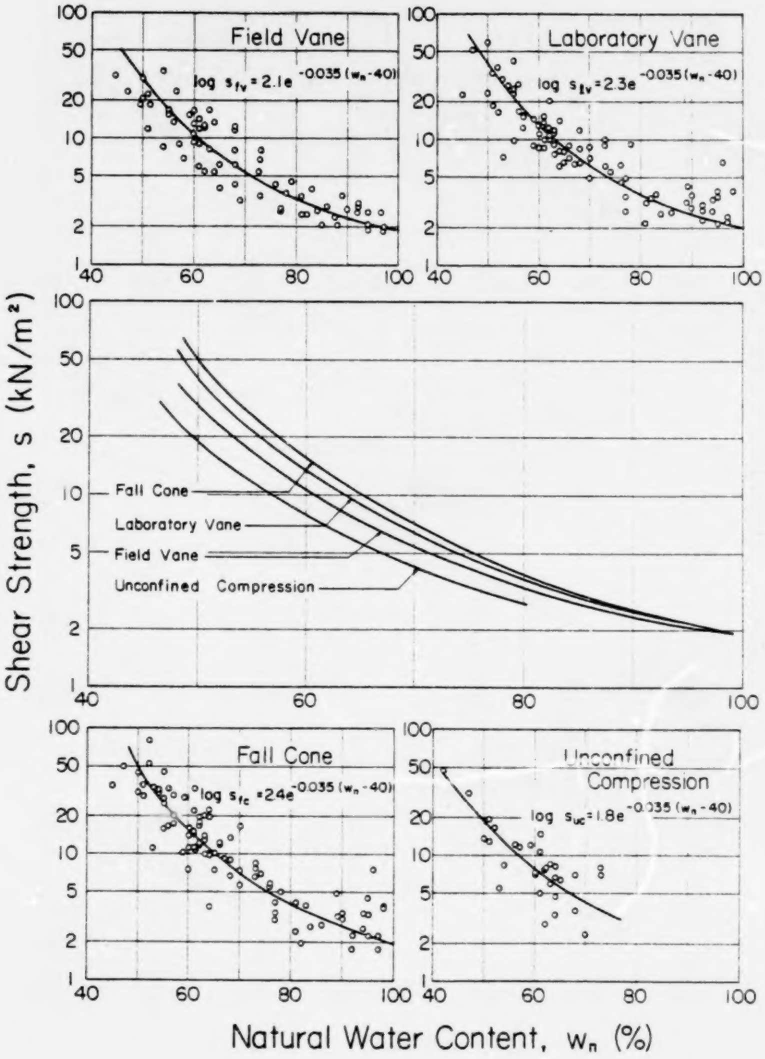

Figure 9-2. Variation of Shear Strength with Natural Water Content

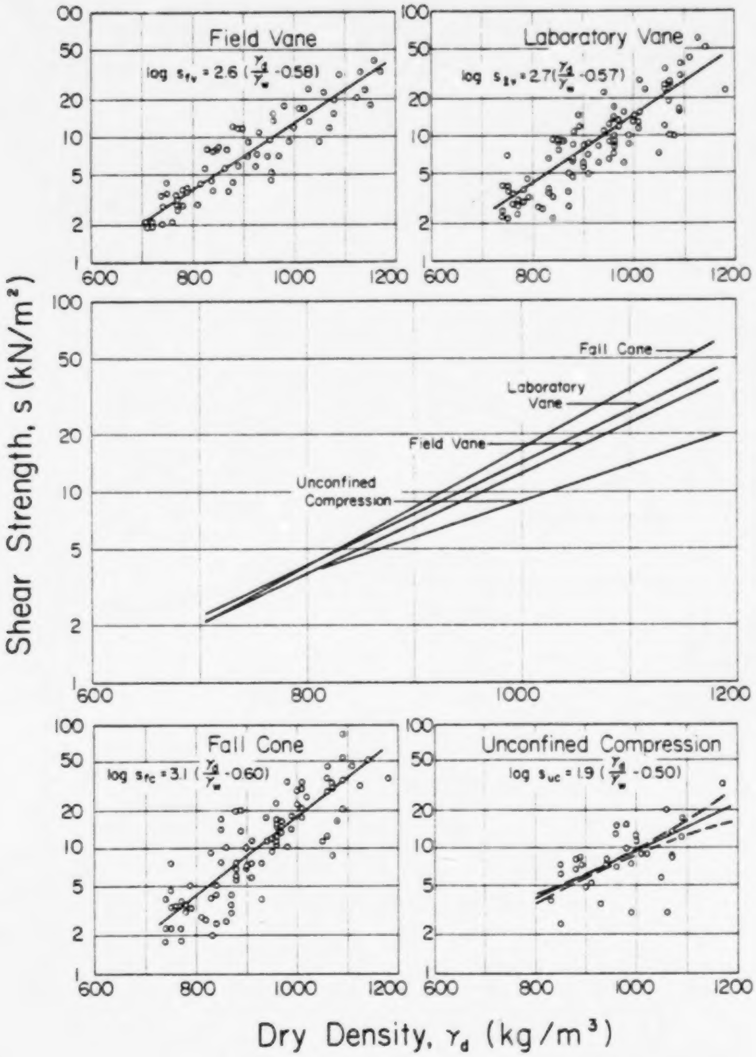

Figure 9-3. Variation of Shear Strength with Dry Density

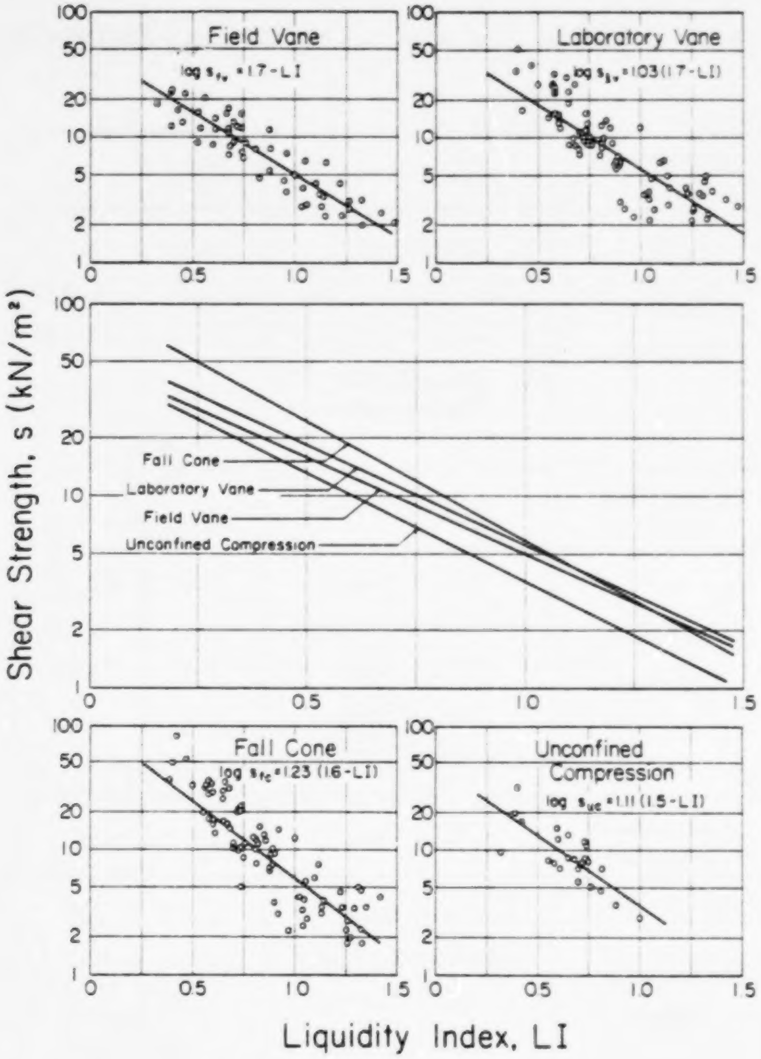

Figure 9-4. Variation of Shear Strength with Liquidity Index

Table 9-1. Values of Coefficients for Strength Relationships

Independent Variables	Type of Test	a_w	b_w
Water Content	Field Vane	2.1	0.035
	Laboratory Vane	2.3	0.035
	Fall Cone	2.4	0.035
	Unconfined Compression	1.8	0.035

Independent Variables	Type of Test	a_γ	b_γ
Dry Density	Field Vane	2.6	0.58
	Laboratory Vane	2.7	0.57
	Fall Cone	3.1	0.60
	Unconfined Compression	1.9	0.50

Independent Variables	Type of Test	a_L	b_L
Liquidity Index	Field Vane	1.00	1.7
	Laboratory Vane	1.03	1.7
	Fall Cone	1.23	1.6
	Unconfined Compression	1.11	1.5

trimming disturbances, which pose particularly difficult problems for soft soils, as was the case for most of the samples tested in this program. As a matter of fact, a detailed study of the individual profiles previously described (and shown typically in Figure 9-1) indicated that in most cases the greatest reductions in unconfined compressive strengths relative to, for example, field vane strengths occurred in the middle (or softest) portion of the dredging layer; in such cases the unconfined compressive strengths were generally about midway between the undisturbed and remolded field vane strengths.

Although the probability of some disturbance of the material during the process of sampling would suggest that the laboratory vane and fall cone strengths should be lower than the field vane strength, the contrary observation may be explained to some extent by (a) the confinement of the samples in the tubes during the laboratory test compared with the relatively free lateral movement of the soil around the blades of the vane during a field test and (b) the difference in the basic nature of the testing procedures (for example, size and height-to-diameter ratio of the two vanes and vane geometry versus cone geometry). Remolded strengths measured by both field vane and laboratory vane are generally found to be in agreement; values obtained by the field vane are usually somewhat lower for the top crust and somewhat higher in the soft zone at depths between 1 and 2 meters. In general, the shear strength values obtained in this experimental program compare well with those reported by the Philadelphia District Corps of Engineers (1969) for samples from four sites along the Delaware River, where shear strengths varied from about 100 psf (5 kN/m^2) to 1000 psf (50 kN/m^2) with an average of approximately 500 psf (25 kN/m^2).

SUMMARY

The strength characteristics of the dredgings studied in the Toledo harbor area are comparable to those associated with fine-grained organic soils with similar water contents and dry densities. Although the shear strength of these materials is generally low shortly after deposition, it increases rather consistently with time. Dredged materials of this nature can be categorized as sensitive, where the sensitivity decreases with increasing dry density. The logarithm of shear strength varied exponentially with the natural water content and linearly with the dry density and liquidity index. In most cases the strength values determined in the field and in the laboratory were found to agree reasonably well, but values measured by means of the unconfined compression test were considerably lower than those measured by all other tests and values measured by the fall cone test were the highest.

SECTION 10

MATHEMATICAL MODEL

As mentioned previously, a major factor that controls the usefulness of landfills composed of dredged sediments is their high water content, which affects both the strength and compressibility of these materials and thereby renders any landfill effectively unusable for long periods of time. In order to better understand the nature of the time-dependent water content changes that take place in the dredged materials after deposition, a one-dimentional (vertical) mathematical model was developed (Krizek and Casteleiro, 1974) (a) to describe the water content distribution in the fill at any time after deposition, (b) to predict the desiccation and consolidation behavior of the dredged materials as a function of time, and (c) to aid in evaluating the different techniques that are available to accelerate the dewatering of the landfill. This model is capable of handling the flow of water through a vertically heterogeneous soil at any degree of saturation, together with the associated desiccation and consolidation processes that may occur simultaneously.

The consolidation of a partially saturated medium leads to a variety of conflicting hypotheses. For example, classical consolidation theory, which deals with time-dependent volume change characteristics, is based on the assumption of a fully saturated soil, and the definition of concepts and coefficients for partially saturated media poses a problem for which only incomplete answers exist. On the other hand, soil scientists have directed much effort to studying flow through partially saturated porous media, but they usually assume that such media have a rigid structure and undergo no volume change during flow. The combination of these two approaches constitutes the essential basis for the mathematical model developed herein.

THEORETICAL DEVELOPMENT

Since the deposition of dredged material in a given containment area usually takes place over a period of several years, each year during which spoil is deposited is termed a cycle and the thickness of the sediment layer at the end of each cycle is assumed to be proportional to the amount of slurry placed in the site during that cycle. Furthermore, upon completion of the first cycle, it is assumed that there exists within the site (a) a fully saturated layer of dredged sediments with the same spatial distribution of void ratio and (b) a free water layer with its lower boundary at the sediment surface and its upper boundary at the same elevation as that of the overflow weir. After a certain period of time, the overlying free water evaporates and the top of the layer begins to desiccate. Due to this desiccation and the possible drainage of water into the underlying soil, the position of the groundwater table will lower and the weight of the sediments comprising the layer will increase due to the loss of buoyancy by the material situated above the phreatic surface, thereby causing the thickness of the layer to decrease. This process of desiccation, drainage, and consolidation continues until the beginning of the next cycle, at which time the site is again inundated and the same steps are repeated.

During this second cycle, an additional sediment layer of some finite thickness is deposited in the disposal area. If the rate of deposition is relatively continuous, it can be assumed that the thickness of this layer will increase linearly, and thus the rate of stress increase on the first layer will be constant. This sequence of activities will be repeated as many times as necessary to fill the site. Hence, the basic phenomenon involved in this process is one of water flowing through a consolidating medium in which the location of the interface between the saturated and the partially saturated zones is unknown and dependent on the properties of the dredged material, weather conditions, the nature of the foundation soils, and the particular stage of the cycle.

The above-described flow of water through a heterogeneous porous medium, regardless of its degree of saturation, was modeled one-dimensionally by a general nonlinear partial differential equation. Then, simplifying assumptions were employed to deduce two nonlinear parabolic differential equations, one for the fully saturated zone and the other for the partially saturated zone. The simplifying assumptions are that (a) the velocity of the solids can be neglected with respect to the velocity of the fluid and (b) the generalized form of Darcy's law holds throughout the process.

The boundary conditions incorporated in the model include those natural conditions which are usually found in the field and certain artificial conditions that can be implemented to accelerate the dewatering process. However, due to a general lack of knowledge about the volume change characteristics of partially saturated soils, this boundary value problem cannot be solved directly; therefore, a step-by-step technique was developed to adjust for the effects of the simplifying assumptions, including the differential pressure increase due to the lowering of the water table during desiccation or due to the deposition of a new layer of sediments during dredging periods.

The step-by-step technique involves a multistage correction procedure and is based on the assumptions that, during a small time increment, the nonsaturated zone of the dredgings is incompressible (i.e. $\partial e/\partial t = 0$) and the total stress acting on the underlying dredgings does not change (i.e. $\partial \sigma/\partial t = 0$); after this time increment, the errors introduced in the results by these two assumptions are corrected. The field equations for the saturated and unsaturated zones of this boundary value problem can be represented by

$$\frac{0.4343\ C_c\ \gamma_w}{(1+e)(\bar{\sigma}_0+\sigma-u)}\left[\frac{\partial u}{\partial t}-\frac{\partial \sigma}{\partial t}\right]=\frac{\partial}{\partial z}\left[k\,\frac{\partial u}{\partial z}\right] \qquad (10\text{-}1)$$

and

$$\frac{1}{(1+e)}\left[\theta\,\frac{\partial e}{\partial t}+C(1+e)\,\frac{\partial \psi}{\partial t}\right]=\frac{\partial}{\partial z}\left[k\,\frac{\partial \psi}{\partial z}+k\right] \quad , \qquad (10\text{-}2)$$

respectively, where z is the vertical coordinate, t is time, e is void ratio, u is the excess pore water pressure, C is the specific water capacity of the dredgings, C_c is the compression index, θ is the volumetric water content, $\bar{\sigma}_o$ is the initial effective stress, σ is the total stress, γ_w is the unit weight of water, k is the coefficient of permeability, and ψ is the soil-water potential (or capillary potential). With the assumptions that $\partial e/\partial t = 0$ and $\partial \sigma/\partial t = 0$, Equations (10-1) and (10-2) can be reduced to two single-variable nonlinear parabolic differential equations that may be solved numerically in the specified time interval. The differential equation governing the saturated phase has the form

$$\frac{0.4343\ C_c\ \gamma_w}{(1 + e)(\bar{\sigma}_o + \sigma - u)} \frac{\partial u}{\partial t} = \frac{\partial}{\partial z}\left[k \frac{\partial u}{\partial z} \right] \qquad (10\text{-}3)$$

and the equation governing the unsaturated domain is

$$C \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left[k \frac{\partial \psi}{\partial z} + k \right] \quad . \qquad (10\text{-}4)$$

EXPERIMENTAL CHARACTERIZATION OF ENGINEERING PROPERTIES

The results of an extensive experimental program allow the development of empirical relationships for various functions occurring in Equations (10-3) and (10-4). In particular, it was found that the saturated permeability, k (in cm/sec), over a void ratio range from 1 to 10 can be reasonably well approximated by

$$\log k = - \left[(0.8\ e^2 - 10.2\ e + 62)^{\frac{1}{2}} \right] \quad . \qquad (10\text{-}5)$$

Based on previous experience with nonsaturated soils, the permeability, k, of these dredged materials in the nonsaturated state can be written in terms of their permeability, k_s, in the saturated condition, the void ratio, e, and the volumetric water content, θ, as

$$k = k_s \left[\frac{1 + e}{e}\ \theta \right]^{3.5} \quad . \qquad (10\text{-}6)$$

From the available test data it was impossible to find a unique relationship between the volumetric water content and the soil-water potential, which, for partially saturated soils, is probably the single most important factor describing their physical behavior. If the volumetric water content, θ, is written as a function of the weight water content, w, as

$$\theta = \frac{G_s}{1 + e}\ w \quad , \qquad (10\text{-}7)$$

a maximum value for θ can be obtained by setting e equal to the final void ratio whereas a minimum is obtained by setting e equal to the initial void ratio. After considerable background work, it was found that the general water retention characteristics of the dredged materials under consideration can be reasonably well represented by

$$\theta = \theta_s \exp\left[-\frac{\mu\psi}{\psi_{cr}}\right] + \theta_{cr}\tanh\left[\frac{\nu\psi}{\psi_{cr}}\right] \quad , \qquad (10\text{-}8)$$

where ψ is the soil-water potential, θ_s is the volumetric water content at saturation, θ_{cr} is the limiting or air-dry volumetric water content, ψ_{cr} is the limiting or air-dry soil-water potential, and μ and ν are two empirical material-dependent parameters. There were three principal reasons for choosing this particular relationship. First, it complies directly with the specific water capacity requirement that $C \rightarrow 0$ as $\psi \rightarrow \infty$; second, it was convenient to program; and third, it applies reasonably well to many other soils. The specific water capacity, C, can be derived from Equation (10-8) and has the form

$$C = -\frac{\mu\theta_s}{\psi_{cr}}\exp\left[-\frac{\mu\psi}{\psi_{cr}}\right] + \frac{\nu\theta_{cr}}{\psi_{cr}}\operatorname{sech}^2\left[\frac{\nu\psi}{\psi_{cr}}\right] \quad . \qquad (10\text{-}9)$$

It has been found that the relationship between θ_s and θ_{cr} for most of the dredged materials considered herein is approximately linear; this means that the air-dry water content of a given dredged material can be determined from a knowledge of its minimum void ratio at saturation.

The relationship between the compression index, C_c, and the void ratio, e, in this model has the form

$$C_c = 0.01\ (37\ e - 7) \quad . \qquad (10\text{-}10)$$

However, because e is a function of time, the partial derivative of C_c with respect to time is generally not zero. The spatial distribution of the compression index was assumed to be constant during any given time increment, and an appropriate adjustment was made after each time step. Since no data were available to describe the compressibility of the unsaturated dredged materials, it was assumed that the only volume change in the partially saturated zone resulted from the increase in the total stress at the end of the step; this implies that any reduction in void ratio due to an increase in the soil-water potential is neglected.

The heterogeneity of the deposit in the vertical direction is considered by incorporating the concept of scale heterogeneity in the model. Although this concept is widely employed by soil scientists, the difficulties in characterizing the heterogeneity of these dredged materials precluded its practical application, and only initially homogeneous deposits are considered in this work. Of course, the deposit becomes heterogeneous as the processes of desiccation and consolidation take place.

NUMERICAL SOLUTION OF FLOW PROCESS

The solutions to the nonlinear boundary value problem characterized by Equations (10-3) and (10-4) were determined by means of a finite difference technique. The Crank-Nicolson scheme was employed in conjunction with mixed boundary conditions in such a way that both the governing equation and the surface condition are applied at points on the boundary. The governing differential equations and the boundary conditions were expressed in terms of dimensionless parameters. Moreover, a reduced time factor was introduced in the definition of the dimensionless time variable in order to allow the real time increment to be modified without changing the dimensionless time increment; accordingly, the program could be written to allow for an automatic change of the reduced time factor, if necessary, to enhance convergence. The continuity condition at the interface between individual layers was treated in essentially the same manner.

A noniterative Gaussian elimination method was used to solve the banded coefficient matrix associated with the system of linear algebraic equations that results from the technique applied to discretize the boundary conditions. Test equations were incorporated to guarantee stability of the computational process, which is performed on a digital computer. The time and expense required to obtain the desired information from this mathematical model on the computer were found to be very large (on the order of an hour or more on a CDC 6400), particularly if several cycles are considered.

RESULTS

This mathematical model was used to make settlement predictions at various points in the Penn 7 Site where several measurements have been made since 1972, when the deposition of dredged sediments in this area began. At the time when these computations were performed, the dredging history of this site covered two seasons (September 1972 to December 1972, and June 1973 to August 1973). An average layer thickness for each of these two dredging cycles was calculated by converting the bin-measure volumes actually pumped into the site (Boresch, Personal Communication, 1974) to disposal-site volumes; the latter was accomplished by using the conversion factor of 0.65 determined by Krizek and Giger (1974). Furthermore, it was assumed that 5 cm of water overlaid the surface of the sediments at the end of each cycle; this value corresponds to an estimated average that was observed in the field on several occasions. The soil characteristics used in the model were described previously. Since no consistent data were available to characterize the vertical variation of the fill, the dredged material at a given location within the site was assumed homogeneous, which implies that the scale heterogeneity functions are unity.

A number of different boundary conditions were studied in order to evaluate the effect of different boundary conditions on the settlement response, and the results for three such locations (shown in Figure 4-3) in the Penn 7 area are given, together with field measurements, in Figures 10-1 and 10-2. For this purpose the weather conditions, as expressed in terms of a statistical year, were held constant to guarantee a constant evaporation rate for the initially overlying water and thereby allow for a proper relative comparison. Although a variation in the drainage boundary conditions (where k_f and H_f are the permeability and thickness, respectively, of the foundation soil) can lead to noticeable differences in computed settlements when the second or subsequent layers are being deposited and the situation resembles somewhat a conventional consolidation process, the effect of such a variation was found to be small during the stages when evapotranspiration is taking place. Thus, if an improvement in the bottom drainage characteristics is anticipated to enhance the settlement rate of the landfill, such benefit will take place almost exclusively during periods of no evapotranspiration

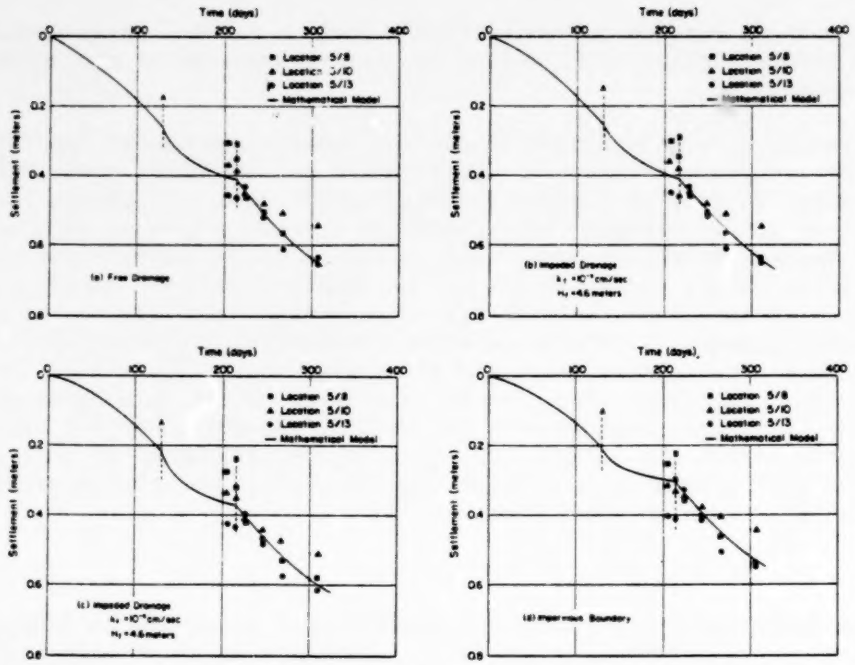

Figure 10-1. Settlement versus Time for No Transpiration and Different Drainage Conditions

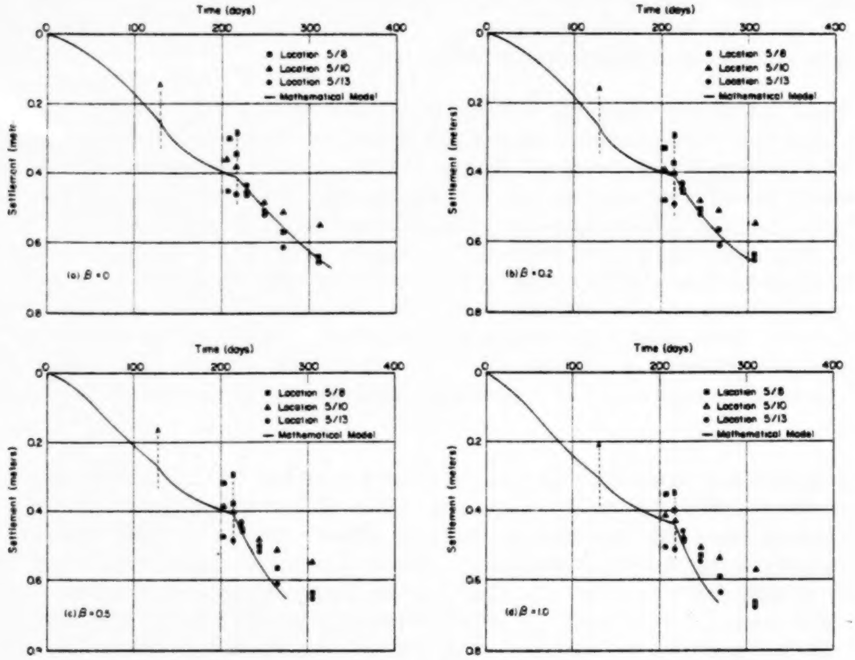

Figure 10-2. Settlement versus Time for Impeded Drainage and Different Coefficients of Transpiration

and, unless these periods are sufficiently long, a careful study should be performed before costly modifications to improve drainage at the bottom boundary are undertaken.

The effect of transpiration on the settlement response of landfills composed of dredged materials was investigated for different coefficients of transpiration, β, with an impeded drainage condition at the bottom boundary. In this study it was assumed that vegetation starts to grow as soon as the top layer becomes slightly unsaturated; although this condition may not necessarily exist in all cases, it can be enhanced by seeding. Based on these assumptions, it was found that the use of vegetation with high rates of transpiration appears to offer a relatively effective and inexpensive way to dewater dredge spoil and increase the settlement rate. The results produced by proper vegetation will likely be as good as or better than those obtained by improving drainage conditions at the bottom, and the costs will usually be significantly lower. In general, the greater the percentage of last-stage desiccation with respect to the total time of deposition, the larger will be the consolidation due to evapotranspiration.

SUMMARY

A one-dimensional mathematical model has been developed to describe the desiccation-consolidation response of a landfill composed of maintenance dredgings. This model has the capability of predicting the water content distribution and the settlement response of a landfill at any given time after deposition of the dredged materials, and it can serve to evaluate the various techniques that may be used to accelerate dewatering of the fill. Any type of soil at any degree of saturation can be analyzed, provided the material properties are reasonably well known.

The flow of water through a heterogeneous medium is described by a nonlinear partial differential equation based on the simplifying assumptions that (a) the generalized form of Darcy's law holds throughout the process and (b) the velocity of the solids can be neglected with respect to the velocity of the fluid. Scale heterogeneity functions are incorporated into the model to account for spatially variable soil characteristics, and the combined effects of evaporation and transpiration at the top boundary, as well as drainage conditions at the bottom boundary, are handled in a general way. The solution to this boundary value problem was obtained by means of a step-by-step finite difference procedure. However, due to the nonlinear character of the governing equation, the time required to solve a practical problem was very large.

The settlement predictions calculated by means of this mathematical model were in reasonably good agreement with those actually measured at the Penn 7 disposal site in the Toledo harbor area. Based on the results of a parameter study with varying boundary conditions, it was found that the effects of evapotranspiration on the dewatering process are quite substantial, and the benefits gained by using vegetation with high transpiration rates may be as good as or better than those obtained by improving drainage conditions at the bottom boundary.

SECTION 11

STABILIZATION

The effective stabilization of dredged materials that are placed in diked containment areas poses challenging problems to the engineer, and many different stabilization techniques (such as dewatering by ditching, sand drains, preloading, and evaporation) have been investigated (Garbe and Jeno, 1968; Corps of Engineers, Philadelphia District, 1969; Greeley and Hansen, 1969; Waterways Experiment Station, U. S. Army Corps of Engineers, 1972; Office of Dredged Material Research, 1974). Included herein is a summary of a more detailed study that has been reported by Krizek, Roderick, and Jin, (1974) on the stabilization of dredged materials by use of chemical additives and by evaporation.

TEST PROGRAM

In the chemical stabilization program outlined in Figure 11-1, three main series were conducted; these included flocculation-sedimentation tests, sedimentation-leaching tests, and repeated leaching tests. These three types of test were developed in successive stages wherein the findings of the flocculation-sedimentation tests formed background for the sedimentation-leaching tests, the findings of which, in turn, constituted the basis for the repeated leaching tests.

The addition of a flocculating agent to a soil suspension causes a flocculation or joining together of fine-grained soil particles, thereby increasing the effective particle sizes of the material; these larger flocs then settle more rapidly from the suspension to form a relatively large sediment volume. The admixture of flocculating agents to dredged materials during the process of disposal into a diked containment area can effectively increase the sedimentation rate and consequently decrease the amount of suspended solids in the effluent water. In addition, the flocculation of suspended solids may cause increased retention of pollutants in the disposal area and further improvement in the quality of the effluent water.

A total of 114 individual flocculation-sedimentation tests were conducted with 22 different chemical additives that were selected on the basis of test results from previous nonrelated studies. Grain size distribution curves and sediment volume data were used to evaluate the effectiveness of the various chemical additives on the degree of flocculation and the sedimentation rate of suspended solids. The criteria for evaluating the flocculation effectiveness of these chemicals were (a) percentage of fines that flocculated, (b) initial sediment volume, and (c) color and clarity of the supernatant. Once a slurry has settled in a diked containment area and the

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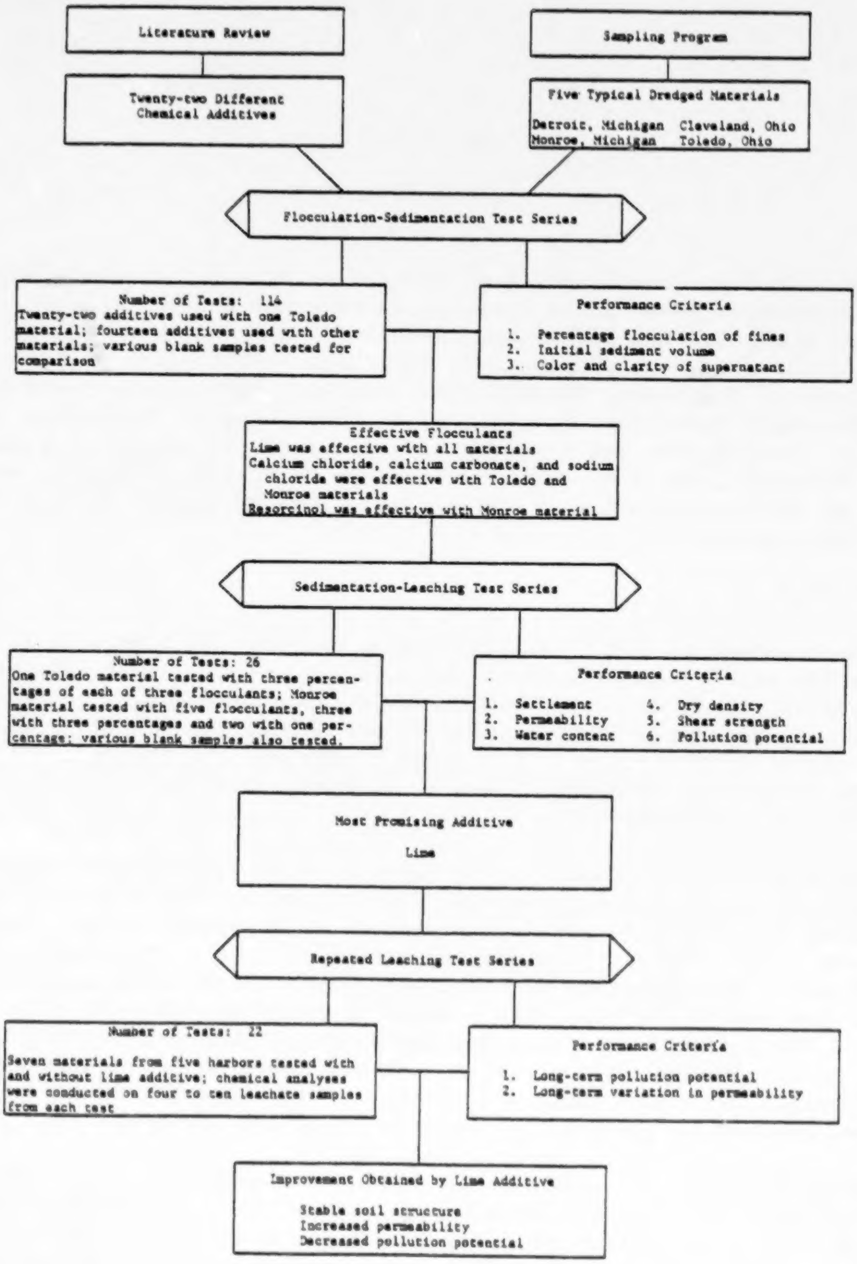
Literature Review
Sampling Program
Twenty-two Different Chemical Additives
Five Typical Dredged Materials
Detroit, Michigan
Cleveland, Ohio
Monroe, Michigan
Toledo, Ohio
Flocculation-Sedimentation Test Series
Number of Tests: 114
Twenty-two additives used with one Toledo material; fourteen additives used with other materials; various blank samples tested for comparison
Performance Criteria
1. Percentage flocculation of fines
2. Initial sediment volume
3. Color and clarity of supernatant
Effective Flocculants
Lime was effective with all materials
Calcium chloride, calcium carbonate, and sodium chloride were effective with Toledo and Monroe materials
Resorcinol was effective with Monroe material
Sedimentation-Leaching Test Series
Number of Tests: 26
One Toledo material tested with three percentages of each of three flocculants; Monroe material tested with five flocculants, three with three percentages and two with one percentage; various blank samples also tested.
Performance Criteria
1. Settlement
2. Permeability
3. Water content
4. Dry density
5. Shear strength
6. Pollution potential
Most Promising Additive
Lime
Repeated Leaching Test Series
Number of Tests: 22
Seven materials from five harbors tested with and without lime additive; chemical analyses were conducted on four to ten leachate samples from each test
Performance Criteria
1. Long-term pollution potential
2. Long-term variation in permeability
Improvement Obtained by Lime Additive
Stable soil structure
Increased permeability
Decreased pollution potential

Figure 11-1. General Outline of Chemical Stabilization Program

dewatering-consolidation process begins, several forces (such as seepage forces, overburden stresses, physicochemical forces, capillary forces, and forces caused by vegetation) act on the sediment. For sediments that are subjected to only their self-weight, the latter two forces are probably dominant in enhancing consolidation, particularly in the top few feet of the fill.

Twenty-six sedimentation-leaching tests were performed with two typical dredged materials to study the effectiveness of chemical additives in stabilizing such materials. The shear strength and the corresponding water content were measured, the coefficient of permeability was calculated, and the water quality of the leachate was analyzed. In addition, an associated sedimentation test without drainage was conducted in order to observe the sediment behavior with time and the effect of the seepage force. All of these parameters were used as criteria to judge the effectiveness of various chemical stabilization methods. These tests were performed in cylindrical sedimentation chambers 18 inches (45 cm) high and 3 inches (7.5 cm) in diameter with a porous stone at the bottom for drainage and an outlet to collect the leachate.

Twenty-two repeated leaching tests were conducted on various typical dredged materials with and without chemical additives to study the long-term pollution potential of the leachates; these tests were performed in chambers similar to those described above, except they were 24 inches (60 cm) high and 6 inches (15 cm) in diameter. In addition, the hydraulic gradient was varied to assess its effect on the pollution potential of the leachates. Under some conditions a substantial volume of water might pass through the deposited sediments and enter the foundation soils underlying a diked containment area, and the possible pollution of the groundwater by these leachates could pose a problem. The contaminants carried by a leachate depend on the composition of the dredged material and the chemical additive, as well as on the physical, chemical, and biological activities that take place within the landfill. Since the repeated leaching tests conducted in this experimental program frequently lasted several months due to the low filtration capacity of the dredged materials, biochemical reactions might have taken place during the tests; however, only chemical analyses were conducted on the leachates.

Evaporation is known to be a promising technique for the economical dewatering of dredged sediments within diked containment areas, and an investigation was therefore conducted to evaluate laboratory and field evaporation from dredged materials and the associated strength gains and water retention curves. A knowledge of the soil-water potential of dredged materials provides the background for a better understanding of the material behavior during the evaporation process.

Three different series of laboratory evaporation tests were conducted. The purposes of the first series were (a) to study the rate of water loss from dredged materials from several different areas and (b) to determine the effect of mixing on the rate of water loss; seven different materials were tested under the same conditions of temperature and relative humidity. The second series of laboratory evaporation tests was directed toward (a) evaluating the influence of sample thickness and surface area on the rate of water loss, (b) observing crack sizes and crack patterns, and (c) determining shear strength gains in the drying soils. The objectives of the third series of tests were (a) to study the effect of lime (CaO) on the water losses, shear strength, deformation, and cracking patterns of the sediments, (b) to obtain additional data to help in interpreting the results of the previous laboratory evaporation tests, and (c) to serve as a guideline for the interpretation of the field evaporation test data. All tests were performed either in glass containers 6 inches (15 cm) high and 6 inches (15 cm) in diameter or in plastic pans 18 inches (45 cm) by 13 inches (33 cm) in areal extent and 4 inches (10 cm) high; the average temperature and relative humidity were about 78°F and 35%, respectively.

Two series of field evaporation tests were conducted in the Toledo area. Both of these test programs were designed to study the strength and deformation behavior of dredged materials subjected to the climatic conditions at Penn 7 (average temperature about 73°F; average relative humidity about 65%, and total precipitation about 9 inches (23 cm) during both testing periods). Relatively small-scale tests were used to obtain better control of sediment thickness, drainage conditions, and lime (CaO) treatment. In the first series 12 drums (22 inches (56 cm) in diameter and 35 inches (88 cm) in height) were used; five of these had perforated bottoms and sand filters to allow drainage during the test period, which began on August 1, 1973, and continued for 14 days. The second series of ten field evaporation tests was conducted at the same site and with the same drums, but greater sample depths were used and a longer test period of 113 days (August 15 through December 5, 1973) was allowed.

RESULTS

Described briefly in the following paragraphs are the major results that were obtained from these various series of tests. As mentioned previously, the parameters involved in each successive test sequence were selectively chosen from the results of the preceding series.

Flocculation-Sedimentation

Calcium oxide and calcium chloride were found to be effective flocculants for most of the dredged materials; the supernatants were colorless and clear for all of the samples tested. The chemicals o-nitrophenol, p-nitrophenol, and tri-nitrophenol were effective flocculants and the supernatants were clear, but they exhibited yellow and pink coloration; this visual pollution of the effluent and the toxicity of the chemicals make them undesirable as practical flocculating agents. Similarly, acetic acid, phosphoric acid, sulfuric acid, nitric acid, hydrochloric acid, and aluminum sulfate were all found to be effective flocculants, but the supernatants became cloudy and had a brownish-yellow coloration after a day of settling. Calcium carbonate was also quite effective as a flocculant for three of the five materials tested, and sodium chloride was effective with two, but the supernatants remained cloudy with both chemicals. The organic chemicals p-benzoquinone, pyrogallol, polyvinyl alcohol, and krilium were not effective flocculants. Resorcinol was effective with only one of the dredged materials and the supernatant remained cloudy.

Sodium hydroxide, potassium hydroxide, and sodium hexametaphosphate (Calgon) were found to be good dispersing agents. Considering the initial sediment volume data and general observations, the higher percentages of organic substituted benzene ring compounds (7 millimole/m.e. or about 10% by weight of the solids) had a better flocculating effect than did the lower percentages of the same organic compounds. According to reports by the Dow Chemical Company, their polymers Purifloc C-31 and Separon 273 are effective flocculants for dredging slurries at 0.4 to 20 grams per liter concentration; hence, these chemicals are promising flocculants for dredge overflow and weir outflow treatments. After studying the test results of this program and comparing the engineering characteristics of the five dredged materials tested, it was found that the coarser dredged materials are less affected by chemical additives.

Sedimentation-Leaching

A comparison of the observed sediment volume versus time relationships for the 26 samples tested suggests the following conclusions. For both of the lime (CaO) treated samples it was found that the sedimentation process was shorter than that of the nontreated samples and a more stable and larger sediment was formed. This is probably due to the flocculation and cementation effects of the lime. The sodium chloride (NaCl) treatment, on the other hand, led to inconsistent results; in one case there was no improvement at all whereas in the other cases some improvement was observed. Calcium chloride ($CaCl_2$) and resorcinol ($C_6H_4(OH)_2$) gave virtually no improvement in any case; this may be due to the fact that the chosen concentrations were larger than 50 grams per liter used in the flocculation-sedimentation tests. In general, all chemicals appeared to be more effective when used with finer-grained materials.

Downward seepage forces would logically tend to densify dredged materials as leaching takes place, and the densities of the samples in sedimentation-leaching tests were indeed found to be higher than those of the corresponding samples in sedimentation tests only. In addition, even though the treated samples exhibited lower densities than the untreated samples in the sedimentation tests alone, they ultimately achieved higher densities when subjected to leaching; this suggests that the effects of seepage forces are greater than those of physicochemical forces. The permeabilities of the lime, calcium carbonate, and sodium chloride treated samples were substantially higher (at least by an order of magnitude) than those of the untreated materials; this is evidently due to flocculating effects which were insignificant for the other chemicals.

Shear strength and dry density were expected to increase as leaching approached completion and capillary tension became more effective. However, this was not the case for lime treated materials, which in all cases exhibited lower densities than untreated materials. At a water content of about 150%, it was found that the cementation effect of the lime was too small to affect the shear strength, but at water contents of about 30%, cementation does substantially increase the strength of the same material approximately proportionally to the amount of lime used. Calcium carbonate treatment resulted in a slight increase in strength whereas sodium chloride had a decreasing effect on strength when compared with the results of untreated materials; this is perhaps due to the deflocculating effect at higher percentages of sodium chloride.

The frequent scatter in the results of the chemical analyses of the leachates is due in large part to the heterogeneous nature of the dredged materials; although this scatter makes it somewhat difficult to draw specific conclusions, it is possible to infer general trends. For example, for chemically treated materials a larger sediment volume is formed at the beginning due to the flocculating effect of the additive. Thus, the fine solids in suspension pass more readily through the pores, thereby resulting in higher suspended and total solids contents for treated than for untreated total and suspended solids contents.

For those flocculants that completely dissolve in the sample (for example, sodium chloride or calcium chloride) the associated leachate usually contained higher amounts of dissolved solids. Moreover, the concentrations of volatile solids and suspended volatile solids in the leachates of the treated materials increase approximately proportionally to the increases in the total solids and suspended solids contents of the treated materials. No general trend can be associated with the pH values; this could be due to the biochemical reactions that took place during testing. The silica content related essentially to the total solids content for each material tested, and no significant variation was observed. The leachates of the lime, calcium carbonate, calcium chloride, and sodium chloride treated samples were found to exhibit increases in calcium and sodium ion concentrations, and these increases were directly related to their respective additives. On the other hand, the ion concentrations on a wet weight basis increase sometimes for total iron and potassium but no significant variation was manifested on a dry weight basis; this may imply that these ions are associated with the passage of solid particles during the process of leaching. The opposite phenomenon was observed for the concentrations of copper, cadmium, lead, and mercury ions; this suggests that these ions may be dissolved in the solution. Based on chemical analyses of the leachates, it appears that none of these additives causes any significant changes in the water quality of the leachates, except for an increase in the solids content due to flocculation and an increase in the specific ion concentration that is directly related to the additive used in the treatment.

Repeated Leaching

Based on 22 individual repeated leaching tests that were conducted on seven different materials with and without lime treatment under different hydraulic gradients, it was found that the leachates from the well-graded coarser dredged materials had lower total solids contents than those of the finer more cohesive materials; this may be due to the presence of fewer fines and more nonactive particles in the coarser samples. An increase in the hydraulic gradient was observed to be associated with an increase in the final percentages of solids, and, in general, the leachates of lime treated samples had a slightly greater solids content. For untreated, undisturbed samples, the solids content of the leachates seemed to decrease with an increase in the volume of water drained; a similar trend was observed with the turbidities of the leachates. The slightly basic pH values did not change significantly during leaching; this could be due to the effect of the slightly basic deionized filling water. The concentrations of metals, such as calcium, copper, total iron, potassium, sodium, and lead, are comparable to those of field samples of water from the wells in Penn 7. The permeability of these sediments decreased slightly with time as leaching progressed, probably due to seepage effects.

For the lime treated, undisturbed sediments, the volatile solids contents of the leachates were higher than in the case of the untreated samples because of the greater removal of organics from the sediments by calcium ions. Moreover, the total iron, potassium, and sodium ion concentrations of the leachates were lower than those of untreated materials; this may be due to the removal of organics by the calcium ions or to ion fixation. Since lime treatment introduced a larger amount of calcium ions in the leachate, the pH was increased to about 12 at the beginning of the test and the permeability increased by a factor of about ten relative to the permeability of untreated materials.

In summary, the leachates of dredged materials placed with or without chemical additives in diked containment areas do not appear to cause any serious pollution problems; this is due in large part to the fact that the permeability of most silty-clay dredged materials is very low, as compared with that of sanitary sludge, and the groundwater is able to adequately dilute the relatively small amounts of contaminants that are leached from the solids.

Evaporation

In the first series of laboratory evaporation tests, the initial rate of water loss increased with increasing initial water content and decreased with increasing clay content, and there was no significant difference in the rate of water loss for mixed and unmixed samples. This may be due to the infrequent mixing and the high initial water content of the samples. Despite this observation for a limited series of tests, there is considerable evidence (Garbe and Jeno, 1968; Greeley and Hansen, 1969; Office of Dredged Material Research, 1974) to suggest that mixing substantially increases the rate of water loss due to evaporation. For any given sample in the second series, the rate of water loss was essentially constant at the beginning of the test period, and higher initial rates of water loss occurred with the thinner samples. Shear strengths increased rapidly with drying; after about 40 days, strengths were greater than the measuring capacity of the equipment used (4000 psf or 192 kN/m^2). The results of the third series of laboratory tests indicated that, in general, the addition of lime (CaO) to the materials does not change the initial rate of water loss, but it does reduce the final rate. The addition of lime greatly increases the gain in shear strength with time.

From the results of the first series of field experiments it was found that the drained samples manifested greater final shear strengths with the greatest shear strengths being found in the samples with the smallest initial heights; this was undoubtedly due to the higher degree of consolidation caused by seepage forces and capillary stresses. The strengths of undrained samples were essentially the same and insignificant, regardless of the initial depth of material and the degree of lime treatment. In the case of the drained samples, lime treatment resulted in lower shear strengths; this was apparently caused by a reduction in the degree of consolidation during the test period.

Results from the second series of field evaporation tests indicated that the thinner samples developed wider and deeper cracks during drying; this may be due to a higher thermal gradient causing a higher rate of water loss. Lime treatment resulted in fewer, but larger, cracks in the drained samples. Except for the sample with the lowest water content, no cracks formed in the undrained sediments. Under undrained conditions, lime treatment resulted in low strengths in the upper portions of the samples.

SUMMARY

Among the many effective flocculants, calcium oxide and calcium chloride are the most suitable from the viewpoint of coloration and clearness of the supernatant. Upon studying the test results of this program and comparing the engineering characteristics of the five dredged materials tested, it was found that the coarser dredged materials were less affected by chemical additives. Based on an overall comparison of all additives tested, lime appears to be the most effective; it has the ability to decrease the long-term rate of volume change, increase the permeability, and retain some of the pollutants. Although the addition of lime causes a reduction in strength and an increase in the calcium ion concentration, it can alter the sediments favorably for further stabilization, such as compaction. The results of repeated leaching tests indicate that the leachates of chemically stabilized dredged materials do not constitute a very serious potential pollution hazard; in particular, if additives such as lime are used, the pollution potential will likely be reduced. Previous experience suggests that the rate of water loss due to evaporation can be increased substantially by mixing the sediments and destroying the crust that forms at the surface. If the sediments are not mixed, the exposed surface area per unit volume of dredged material for evaporative purposes will be dictated largely by the formation of shrinkage cracks and the depth of the layer.

SECTION 12

SYNTHESIS

Synthesized in this section are the major results of an extensive study of the dredging and disposal problem in the United States; of particular concern in this work is the potential usefulness of dredged materials as landfill. The overall dredging and disposal problem is first placed into national perspective by a concise review of the magnitudes and types of dredged materials that are encountered throughout the country, the types of equipment that are employed, the types of disposal that prevail in various regions, the environmental and legal constraints that exist, the beneficial uses that can be made of dredge spoil, and the general economics of the different alternatives. Then, the detailed findings of a concentrated research effort in the Great Lakes area are described; this latter part of the study comprised the thrust of the research program, and it was directed toward a quantitative assessment of the engineering characteristics (strength, permeability, compressibility, consolidation, etc.) of typical Great Lakes sediments as they pertain to the construction of landfills.

NATIONAL PERSPECTIVE

The importance of navigable waterways and harbors to the economic growth of the United States is manifested by the fact that waterborne commerce now exceeds 1.5 billion tons per year; this represents more than an 80% increase in total tonnage during the 20-year period from 1950 to 1970, and future projections indicate that this important role will persist in the years to come. In order to maintain the almost 32,000 kilometers (20,000 miles) of waterways and 1,000 harbors, approximately 230,000,000 cubic meters (300,000,000 cubic yards) of bottom sediments are dredged annually, and an additional 60,000,000 cubic meters (80,000,000 cubic yards) are removed to develop new projects (Boyd et al, 1972). Although some of this work is performed by private contractors, the development and maintenance of the navigable waterways in the United States rest with the U. S. Army Corps of Engineers. Current annual costs for these operations amount to about \$200,000,000 with the unit cost ranging from about 20¢ to more than \$10 per cubic meter. Presented herein is a brief overview of the current dredging and disposal problem in the United States; addressed in a very general way are the various types of materials that are encountered, the techniques used to dredge and dispose of these materials, the environmental and legal constraints that must be satisfied, and the economic considerations that are involved.

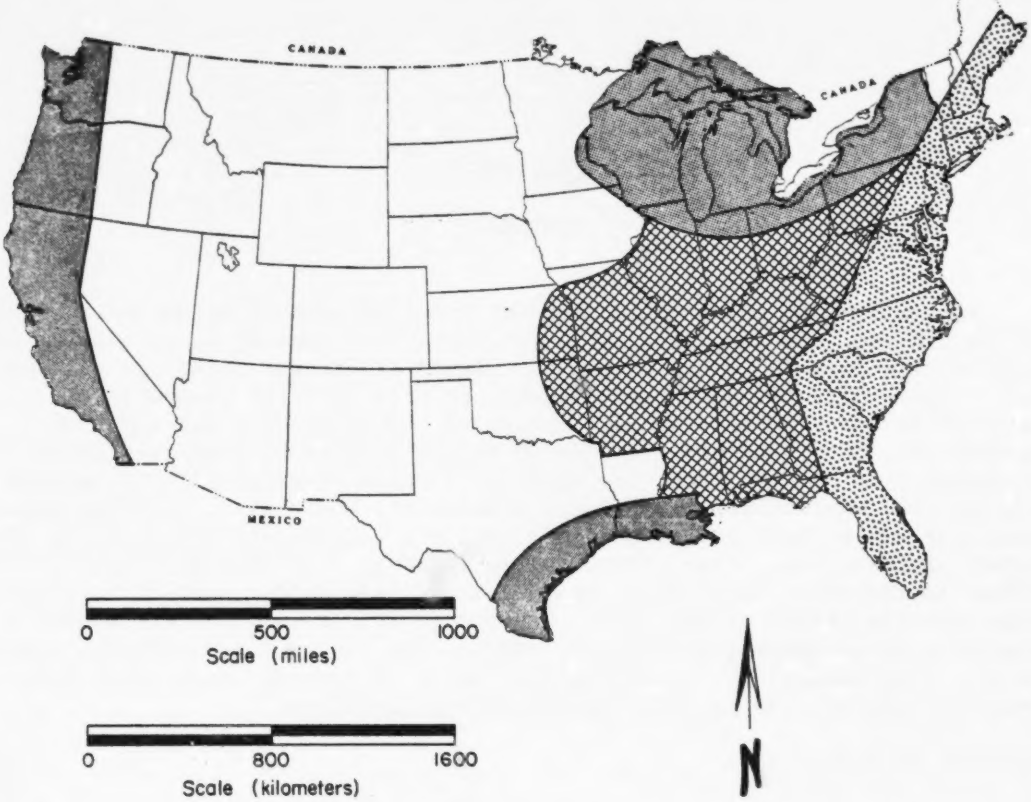

Figure 12-1. Major Regions of Dredging Activity in the United States

Major Geographic Regions

As illustrated in Figure 12-1, the major regions of dredging operations throughout the continental United States can be arbitrarily grouped into the East Coast, Great Lakes, Southeast and Central, Gulf Coast, and West Coast. The East Coast region includes primarily the New England area and the harbors of New York, Philadelphia, Baltimore, Norfolk, Wilmington, Charleston, Savannah, and Jacksonville. The main harbors in the Great Lakes region are Buffalo, Huntington, Detroit, Chicago, and St. Paul. The Southeast and Central region includes Nashville, Mobile, Vicksburg, Memphis, St. Louis, Rock Island, Kansas City, and Tulsa. The Gulf Coast region consists essentially of the harbors and waterways serving New Orleans and Galveston. And the West Coast region includes Seattle, Portland, Sacramento, San Francisco, San Diego, and Los Angeles. Table 12-1 gives a breakdown of the approximate quantities and percentages of dredged materials that are handled in each region.

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Table 12-1. Summary of Dredged Material Volumes by Category and Region

			Quantity of Dredged Materials in Millions of Cubic Yards and Percent of Total Volume											
			East Coast		Great Lakes		Southeast and Central		Gulf Coast		West Coast		Category Totals	
Type of Dredge		Hopper	19.2	35	7.5	54	2.4	3	28.8	26	12.5	44	70.4	24
		Sidecaster	0.4	1									0.4	
		Pipeline	29.6	55	0.4	3	88.7	96	79.9	74	6.8	23	205.4	69
		Clamshell and Bucket	1.6	3	1.5	11	0.2	—			0.2	1	3.5	1
		Dipper			0.8	6							0.8	—
		Mixed	3.1	6	3.6	26	1.1	1			9.2	32	17.0	6
Grain Size Classification		Mud, Clay, Silt, Topsoil, Shale	18.9	35	1.6	12	18.6	20	33.0	30	7.4	26	79.5	27
		Silt and Sand Mixed	13.5	25	6.3	46	55.0	60	75.0	69	4.1	14	153.9	52
		Sand, Gravel, Shells	12.5	23	4.9	35	16.0	17	0.7	1	17.1	60	51.2	17
		Organic Muck, Sludge, Peat, Municipal and Industrial Waste	0.4	1	1.0	7					0.1	—	1.5	—
		Mixed	8.6	16			2.5	3					11.1	4
Type of Disposition		Confined	24.8	46	5.2	38	3.9	4	29.0	27	3.9	14	66.8	22
		Unconfined Upland	4.0	7	0.1	1	0.4	—			0.3	1	4.8	2
		Open Water	22.9	43	8.5	61	72.6	79	61.5	56	16.0	56	181.5	61
		Undifferentiated	2.2	4			15.2	17	18.2	17	8.5	29	44.1	15
Pollution Status	Polluted	Confined	7.8	14	4.9	36	2.8	3	6.3	6	2.8	10	24.6	8
		Unconfined Upland	3.3	6									3.3	1
		Open Water	6.2	12	4.6	33	11.6	13	7.0	6	6.4	22	35.8	12
		Undifferentiated					12.0	13	11.2	10	0.4	2	23.6	8
	Non-Polluted	Confined	17.1	32	0.3	2	1.0	1	22.7	21	1.1	4	42.2	15
		Unconfined Upland	0.7	1	0.1	1	0.4	—			0.3	1	1.5	—
		Open Water	16.6	31	3.9	28	61.1	66	54.5	51	9.6	33	145.7	49
		Undifferentiated	2.2	4			3.2	4	7.0	6	8.1	28	20.5	7
		Regional Totals	53.9	18	13.8	5	92.1	31	108.7	36	28.7	10	297.2	100

Note: The basic information summarized in this table was taken from the report by Boyd, Saucier, Keeley, Montgomery, Brown, Mathis, and Guice

Types of Dredging Equipment

The types of dredging equipment used by both the Corps of Engineers and private contractors are discussed briefly in the context of the average annual quantity of maintenance dredging associated with each type, and the results are summarized in Table 12-1. Although this table shows only that equipment used in maintenance dredging operations, it is a fairly accurate reflection of the types and relative usage of each type for all dredging activities.

Hopper Dredge

All hopper dredges are owned and operated by the Corps of Engineers, and their use is confined primarily to maintenance operations in the coastal regions (45,000,000 cubic meters or 60,000,000 cubic yards per year) and the Great Lakes region (5,700,000 cubic meters or 7,500,000 cubic yards per year). Although hopper dredges have traditionally disposed of their materials in open water, the situation is changing somewhat; due primarily to environmental concerns over open water disposal, several hopper dredges (especially those operating in the Great Lakes) have been modified to allow direct pumpout for land disposal, and other hopper dredges have been modified for sidecasting to allow such disposal procedures as beach nourishment.

Pipeline Dredge

Hydraulic pipeline dredging by dustpans and cutterheads accounts for approximately 70% (157,000,000 cubic meters or 205,000,000 cubic yards) of the average annual maintenance dredging. Dustpan dredges are all owned by the Corps of Engineers and are used almost exclusively for channel maintenance in the Mississippi and Missouri Rivers; they account for a dredging volume of less than 40,000,000 cubic meters (50,000,000 cubic yards), most of which is deposited in open water. Since cutterhead dredges, which are used for both maintenance and new work, are not all owned by the Corps of Engineers, the remaining volume of about 115,000,000 cubic meters (150,000,000 cubic yards) does not necessarily represent the total quantities dredged by all cutterheads (but rather that volume dredged by those cutterheads owned and operated by the Corps of Engineers).

Sidecaster Dredge

Sidecaster hydraulic dredges are all Corps-owned and are used primarily for maintenance dredging in the East Coast region. Although they operate in somewhat the same way as hopper dredges, they differ in that the dredging and disposal operations are carried on simultaneously with the dredged materials discharged to the side of the navigation channel. Sidecaster dredging averages less than 750,000 cubic meters (1,000,000 cubic yards) per year, and, as far as can be determined, all disposal operations fall into the open water disposal category.

Dipper, Clamshell, and Bucket Dredges

Dipper, clamshell, and bucket dredges collectively account for an annual average of approximately 3,000,000 cubic meters (4,000,000 cubic yards) of maintenance dredging. Unlike the dredges described above, these dredges operate on mechanical, rather than hydraulic, principles. Most mechanical dredging is done for the Corps of Engineers by private contractors. Although the rate at which the materials are removed by these dredges is small compared to that of hydraulic dredges, they are ideally suited for working in small areas such as harbors and slips; the dredged materials are usually placed in barges or scows and transported to the disposal site, which may be on land or in the water.

Grain Size Classification

As shown in Table 12-1, the types of dredged materials may be classified into five broad categories. By far the largest category (approximately) 118,000,000 cubic meters or 154,000,000 cubic yards per year) is that termed mixed sand and silt; about 60% of these materials come from the coastal areas and 40% are from the inland rivers and the Great Lakes. Approximately 23,000,000 cubic meters (30,000,000 cubic yards) per year of sand, gravel, and shell are dredged from the coastal regions while about 16,000,000 cubic meters (21,000,000 cubic yards) are dredged from the inland waterways and the Great Lakes; indeed, the moving sand bottoms of many navigable rivers have been a long-exploited supply of sand and gravel for construction purposes. Mud, clay, silt, topsoil, and shale account for 60,000,000 cubic meters (80,000,000 cubic yards) per year, about 46,000,000 cubic meters (60,000,000 cubic yards) of which are dredged from the coastal areas and the rest from the inland rivers and Great Lakes. Although organic muck, sludge, peat, and municipal-industrial wastes account for only 1,200,000 cubic meters (1,500,000 cubic yards) per year, some of the more pressing environmental problems are associated with these materials.

Types of Disposal

In the past dredged materials were deposited at selected disposal sites near enough to the dredging site to minimize disposal cost, but sufficiently far from beaches, water intakes, etc., to negate any adverse effects on these facilities; within these constraints the decisions regarding the means of disposal (open water, confined, unconfined upland, and undifferentiated) were based primarily on economic considerations. In recent years, however, confined disposal has increased in importance because environmental factors have introduced additional constraints. Approximately 200 active Corps of Engineers dredging projects rely in whole or in part on the confined disposal of dredged materials, and almost 3000 hectacres of new land are acquired each year to contain the volume of material generated solely by maintenance operations (Kirby, Keeley, and Harrison, 1973). Notwithstanding this trend, the data in Table 12-1 show that open water disposal is still used for over 60% of the materials.

Pollution Status

When the concentration of one or more of seven selected chemical parameters exceed prescribed limits, dredged sediments are considered to be polluted according to current standards. Table 12-1 indicates the approximate quantities of dredgings that are considered polluted and unpolluted in each region. Almost 30% (66,000,000 cubic meters or 87,000,000 cubic yards) of all maintenance dredgings are considered to be polluted, but the percentage in the Great Lakes region is more than double this average percentage.

Of the 140,000,000 cubic meters (182,000,000 cubic yards) per year of maintenance dredgings reported as being placed in open water, approximately 20% (27,000,000 cubic meters or 36,000,000 cubic yards) are classified as polluted. Confined disposal accounts for almost one fourth of the total amount of maintenance dredgings with the largest percentages being handled in the East Coast and Great Lakes regions.

Beneficial Uses

In contrast to the traditional characterization of maintenance dredgings as an undesirable waste product, there are many beneficial uses that can be made of dredged materials. Perhaps the most obvious of these is their use as a fill material to form islands or waterfront developments. Although most maintenance dredgings cannot be classified as ideal fill materials, history has witnessed the development, either intentional or unintentional, of a number of man-made landfills which have been used to great advantage; in this regard virtually every major harbor in the United States includes terminals and piers that are built on landfills of dredged materials, and many airports and highways, as well as recreational areas, are founded at least in part on dredge spoil. There is also a significant potential for the use of dredged materials in beach nourishment, creation of wildlife refuges, bottom substrate enhancement, and strip mine reclamation. Very possibly nutrient enriched dredged materials could be used to improve the sterile wastes that will evolve from the processing of oil shale. As mentioned earlier, dredged sands and gravels have been used as construction materials for many years, and there is every indication that this trend will continue.

Environmental and Legal Constraints

Some of the early concerns over possible adverse effects of dredged materials on aquatic environment appear to have arisen in the Great Lakes area, where in 1966 the Corps of Engineers started to investigate feasible alternatives to open water disposal at a few selected harbors. The increasing awareness of this problem by environmental groups and the reaction of various public organizations eventually led to a jointly sponsored pilot study by the Corps of Engineers and the Environmental Protection Agency in 1969 to assess the impact of open water disposal on the lake environment. As a consequence of this pilot study, it was recognized that the problem is extremely complex and in need of a large-scale research effort over a period of several years; in the interim it was concluded that contained storage for a period of a few years would greatly enhance water quality in the Great Lakes.

This work led to the enactment of the River and Harbor Act of 1970 (Public Law 91-611), wherein the Congress authorized the Secretary of the Army to construct, operate, and maintain contained disposal facilities with a ten-year absorption capacity in the Great Lakes area. At that time, the Great Lakes area was apparently the only region in the United States where, in the interest of pollution abatement, specific legislation was enacted to provide for confined disposal of polluted dredge spoil regardless of the local cooperation requirements of existing federal navigation projects or the resulting increase in dredging and disposal costs. In the last few years, however, the disposal of dredged spoil has become a problem of national concern, and there have been several instances where harbors and channels have not been dredged because no suitable spoil disposal scheme could be devised to satisfy the constraints imposed by various groups and individuals concerned with the ecologic and aesthetic aspects of the environment and by the variety of new legislation at the federal, state, and local levels.

Three groups of laws involving mandatory, discretionary, and other environmental conditions pertaining to regulations and policies that represent constraints on the disposal of dredged materials are well described in a report by Wakeford and MacDonald (1974). Most of these laws deal in one way or another with policy statements of the U. S. Congress and the various state legislatures; some outline general policies whereas others contain specific prohibitions. In particular, a number of these federal and state laws are concerned with water quality, land use, and the protection of wetlands and coastal areas, and they contain expressions of policy that restrict the disposal and potential usefulness of dredged materials. Water quality criteria often impose severe restrictions on the disposal of dredgings, and turbidity standards for the receiving waters are frequently difficult, if not impractical, to meet.

Once the states have a plan approved by the Secretary of Commerce under the Coastal Zone Management Act of 1972, land enhancement and proposed marketable uses for dredged materials are subject to the legal requirements that (a) major land or water fill operations require a detailed Environmental Impact Statement, (b) the placement of even unpolluted materials in water to make marshes or islands requires prior coordination with various fish and wildlife agencies, and (c) the proposed action must be consistent with the state program for coastal management. However, the Marine Protection Research and Sanctuaries Act of 1972 does not apply to marshes and islands constructed pursuant to an unauthorized state or federal project.

The balance of the federal and state laws dealing with the end use of dredged materials may be characterized as "permit" laws; these laws, all of which require some form of state approval, have been enacted to protect the coastal and wetland areas, to oversee general land use requirements, and to guarantee the preservation of minimum water quality standards. Almost without exception, however, these laws allow the undertaking of justifiable affirmative action programs that are, on the whole, environmentally sound and in accord with the public interest. The temporary storage of dredged materials for several years will, in general, require the protection of wetlands. In such cases county or municipal ordinances usually control the height to which materials may be stored and the restrictions that must be satisfied if the materials exhibit offensive odors. On the other hand, clean materials intended for use in construction are subject to codes of a technical nature only.

With regard to the donation or sale of dredged material, there are a myriad of laws, federal regulations, Army regulations, and Corps of Engineers regulations that describe the types of property that can or cannot be sold or donated and the procedures that are to be followed in either case. In essence, the Corps of Engineers owns that material which is regularly placed on federal lands, but that portion which is surplus to the requirements of the government can be sold or donated. Depending on the statutory authority selected, there are different hierarchies of preferred donees, but the only firm prohibitions contained in these laws are that the material must be sold at its fair market price and that it must not be injurious to the public.

Aside from the various legal constraints, there are many other social and political constraints that influence the potential uses of dredged materials. For example, since maintenance dredgings have an established (though not necessarily justified) reputation of being environmentally detrimental, public reaction is often negative to their disposal near recreational or living areas due to a fear of pollution effects, offensive odors, attraction of undesired insects, and potential diseases that might emanate from such deposits. Further constraints may be imposed by local business interests, such as the possible effect of dredged sand and gravel on the prices of similar materials from commercial pits.

Economics

An assessment of the economics associated with dredging and disposal operations on a broad scale is virtually an impossible task because of the many factors, both technical and nontechnical, that are involved. Although several technical measures (such as automation, improved equipment, better training of personnel, more accurate positioning, use of chemicals, and modification of dredging operations) may improve the economy and environmental acceptability of dredging and disposal operations, the more significant economic factors arise from the nontechnical measures (such as national policy, social acceptance, environmental compatibility, and nature of contractual agreements). For example, a change in the method of payment (based on care and accuracy, rather than primarily on quantity) for dredging may substantially affect current practice on many projects. Since factors such as social acceptance and environmental compatibility are rather subjective, their inclusion in any quantitative economic analysis is invariably based on somewhat arbitrary and often controversial hypotheses, and a change in these basic assumptions may completely alter the economics of the situation.

If the disposal of dredged materials in a given situation presents the alternatives of a containment area and open water deposition at a large distance from the source of the dredgings, the tangible economics revolve around comparing the costs of constructing and maintaining a containment facility (less any benefits realized) and the transportation costs associated with hauling the dredgings to a satisfactory open water disposal point. While it is difficult to generalize the economics of disposal for the above reasons, many projects yield unit costs between \$1 and \$3 per cubic yard for dredging and disposal either in a containment area or in open water; for example, the recent cost of dredging and disposal in the Toledo harbor has been about \$1 per cubic yard for either confined or open water disposal whereas in the Norfolk area ocean dumping costs several dollars per cubic yard and confined disposal costs less than \$1. However, many unit costs for confined disposal exceed \$10 or \$15 per cubic yard; typical examples include some proposals in Baltimore for the disposal of dredgings in abandoned quarries many miles inland and a new ten-year disposal site that will ultimately become usable lakefront land in Milwaukee. Notwithstanding any potential economic advantage of open water disposal, there are many cases where open water disposal is specifically prohibited and no feasible alternative other than confined disposal exists.

GREAT LAKES STUDY

Within the context of the foregoing national perspective, almost 10,500,000 cubic meters (14,000,000 cubic yards) of spoil are dredged annually from more than 100 Great Lakes harbors. Of this volume about one third is considered to be polluted, and virtually all of this polluted spoil is placed in confined disposal areas. Summarized in this section are the salient features of a four-year study directed toward evaluating the potential usefulness of dredged materials as landfill in the Great Lakes region. Although test data on bottom sediments from seven Great Lakes harbors are contained in this study, most of the work, including the instrumented field site, was undertaken in the Toledo harbor area, and the conclusions, although believed to be reasonably applicable to any sediments of a similar nature, are strongly weighted in favor of the conditions experienced in the Toledo area.

Water Quality Aspects of Confined Disposal

The water quality study conducted at the Penn 7 disposal site in Toledo, Ohio, has led to several important conclusions. First, the majority of the pollutants in dredge spoil tend to associate with the solid particles, and the concept of using a diked containment area as a settling basin to retain the polluted solids does effectively improve the quality of the surface waters on the surrounding region. Second, the quality of the effluent that was discharged from the disposal area is similar to that of the ambient river water and slightly better than that of the groundwater. And, third, the spoil retained within the diked enclosure represents a highly concentrated source of pollutants which might leach into the groundwater, thereby reducing to some extent the advantage gained by placing the polluted materials in a confined disposal area in the first place. However, for the particular dredgings investigated, the coefficient of permeability obtained from laboratory tests was found to range from about 10^{-7} to 10^{-8} cm/sec for void ratios between 1 and 2. (Such void ratios are commonly found in hydraulically placed deposits of dredged materials.) For a 10-foot (3-meter) layer of dredged material subjected to a hydraulic gradient of unity, one throughput of leachate would require more than 50 years. On the other hand, field infiltration tests on materials with comparable void ratios yielded permeability coefficients about three orders of magnitude higher; use of these field-measured values would indicate that one throughput of leachate may require as little as one month. The true coefficient of permeability obviously exerts a very strong influence of the groundwater pollution from the disposal area leachates. If the higher permeability should actually prevail, it can be argued that the pollutants might not leach readily from the solids and that the dispersion in the groundwater might be sufficient to reduce the concentrations of pollutants to acceptable levels over a long period of time, whereas if the lower permeability actually exists, the quantity of pollutants entering the groundwater would be so small that effects would certainly be negligible. One advantage demonstrated by the results of the stabilization study is that the addition of lime reduces the amount of pollutants that is leached.

Characterization of Dredged Materials

The characterization tests on the dredged materials obtained from four different disposal sites in the Toledo harbor area indicated that all materials are essentially similar in nature and can be classified as a mixture of organic silts and clays of medium to high plasticity (OH) and inorganic clays of high plasticity (CH), with approximately 60% of the materials tested lying in the first category and 40% in the second. Most of the materials were found to contain about 4% to 8% organic constituents, placing them in the category of intermediate organic soils. Sand, silt, and clay components were present in the approximate proportions of 1:3:2, respectively. The liquid limit of these materials ranged between about 50% and 90% for respective clay contents of 20% and 50% with an approximately linear relationship for intermediate values. The plastic limit ranged between 30% and 50% and was found to be independent of clay content within this range. Since the characteristics of the materials deposited in each of the four Toledo sites were found to be essentially the same, data from all four sites were synthesized and treated as representative of one large site spanning a time period of almost a decade.

Compressibility and Consolidation

Data from an extensive series of conventional consolidation tests on undisturbed samples indicated that the compression index lies between 0.3 and 0.7 and increases linearly with both water content and liquid limit. The secondary compression characteristics were studied by means of long-term slurry and conventional tests, and the deflection-log time response was found to exhibit a consistent, but unusual, pattern wherein the rate of secondary compression, after being constant with log time for a considerable length of time, started to increase and form a second S-shaped curve similar to that associated with the classical response for primary consolidation. The coefficient of secondary compression was correlated with index properties and consolidation stress in order to facilitate a rapid estimate of the magnitude of the secondary settlement. Despite the significant difference in the proportions of secondary and primary compression obtained from slurry and conventional tests, the total settlement per unit height associated with corresponding stress levels is about the same for both tests. However, the times necessary to reach ultimate settlements are shorter in the case of slurry consolidation tests than in the conventional tests. The coefficient of consolidation for these materials was about 0.0006 ± 0.0003 cm^2/sec for all consolidation stresses except possibly the very low values. A comparison of the actual settlement-time response measured in the field with that predicted by the use of classical consolidation theory showed that measured field settlements were considerably higher than those calculated, even for the so-called maximum settlement conditions. However, measured field settlements agreed reasonably well with those calculated by use of an improved mathematical model that accounted more realistically for the actual physical phenomena that occur during the desiccation and one-dimensional consolidation of successive layers of dredged materials as they are deposited periodically in a diked containment area.

Shear Strength

As with virtually all soils, the water content of these fine-grained dredged materials was found to bear a major influence on their shear strength, which is generally very low, and, unless landfills consisting of these materials are adequately drained, they will likely remain soft and weak for many years. The field strengths of these materials increased rather consistently with time for a period as long as ten years, but the rate was rather low (about 4 kN/m^2 or 0.6 psi per year). The logarithm of the shear strength of these dredgings varied exponentially with water content and linearly with dry density or liquid limit, and their strength characteristics are similar to those associated with fine-grained organic soils. Based on measured sensitivity values, these dredged materials can be classified as "sensitive soils." The results of the chemical stabilization study indicated that lime, although generally the most favorable stabilizing agent from an overall point of view, actually reduced the shear strength of these materials somewhat through alteration of the soil structure.

Potential Usefulness of Landfills

Within the context of this four-year study to evaluate the usefulness of fine-grained, polluted, dredged materials for landfill, certain broad conclusions can be advanced. In a relative sense, the disposal of dredged sediments in diked containment areas does improve the overall quality of the surrounding surface waters, but it is not clear whether the degree of improvement realized is sufficient to justify the considerably higher costs involved. In addition, the low initial shear strength of these high-water-content, organic materials under natural conditions, along with their slow rate of strength increase with time and their associated large volume changes, seriously limit the usefulness of landfills composed of dredged materials. Unless special steps are taken to improve the quality of these materials, their use will be restricted largely to wildlife refuges, parks, recreational areas, parking lots, access roads, and the construction of light buildings with flexible structural joints and flexible floors which would allow several inches of total settlement and a few inches of differential settlement.

Improvement Techniques

The improvement of such landfills can be accomplished by use of chemical additives or mechanical methods, such as preloading, sand drains, sand blankets, vacuum drainage, electro-osmosis, or combinations thereof, or by evaporation in conjunction with continuous mechanical conditioning. Another technique for improving the natural soil conditions (that is, the homogeneity of the landfill) within a diked containment area consists of systematically changing the positions of the inflow and outflow points, thereby enhancing the homogeneity of the grain size distribution throughout the site (because larger particles would settle near the inflow point and combine with the finer particles resulting from a previous positioning of inflow and outflow points) and increasing the uniformity of both strength and volume change characteristics.

In general, however, these methods are expensive and a proper cost-benefit analysis will be required to decide whether or not any of them are justified in a given set of circumstances. From a purely technical point of view, the efficient dewatering of dredged materials probably imposes the greatest engineering constraint on their use as landfill materials, and novel techniques for accomplishing this goal at lower costs are highly desirable.

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